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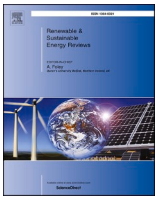

100 key questions to guide hydropeaking research and policy

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ABSTRACT

As the share of renewable energy grows worldwide, flexible energy production from peak-operating hydropower and the phenomenon of hydropeaking have received increasing attention. In this study, we collected open research questions from 220 experts in river science, practice, and policy across the globe using an online survey available in six languages related to hydropeaking. We used a systematic method of determining expert consensus (Delphi method) to identify 100 high-priority questions related to the following thematic fields: (a) hydrology, (b) physico-chemical properties of water, (c) river morphology and sediment dynamics, (d) ecology and biology, (e) socio-economic topics, (f) energy markets, (g) policy and regulation, and (h) management and mitigation measures. The consensus list of high-priority questions shall inform and guide researchers in focusing their efforts to foster a better science-policy interface, thereby improving the sustainability of peak-operating hydropower in a variety of settings. We find that there is already a strong understanding of the ecological impact of hydropeaking and efficient mitigation techniques to support sustainable hydropower. Yet, a disconnect remains in its policy and management implementation.

1. Introduction

Hydropeaking has been receiving increased attention [1–4].

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List of abbreviations

EU	European Union
SDGs	United Nations Sustainable Development Goals
WFD	EU Water Framework Directive

Hydropeaking – rapid and frequent changes in river flow to optimize hydropower operation – is a phenomenon observed globally, primarily associated with large power-generating (storage) dams operated in load-following mode (Fig. 1). Hydropeaking is widely discussed in the context of climate change and the rise of renewables to integrate energy production and demand in the power grid [5,6], and to increase flexibility in the energy system [7,8]. However, the ecological impacts of hydropeaking, including reduction of species abundance [9] and biomass [10,11], lowered primary production [12], and altered assemblages of river fauna and flora [13–15], are of great concern [16–18]. Despite research efforts, many knowledge gaps still need to be addressed to encourage wide-scale implementation of mitigation measures, of which only some examples exist to date [17,19–22].

The current freshwater biodiversity crisis demands that we solve central knowledge gaps to expedite effective policy and management efforts [25–27], particularly given a renewed commitment to hydropower as a green, sustainable, and low-carbon energy source [28–31]. So far, hydropeaking mitigation actions are primarily developed at smaller (national) scales, such as in the Swiss or Italian alps [21,22,32]. To support the wide-scale establishment of targeted mitigation and conservation frameworks in hydropeaked rivers, scientists must tackle the most urgent knowledge gaps for policy and management decisions [26,33]. As these high-priority questions related to hydropeaking have yet to be defined [34], we identify 100 key questions for hydropeaking research.

The 100 questions horizon scan exercise is a popular strategy to identify and prioritize research needs. The 100 questions approach is a process of identifying emerging issues or questions that, if answered, have the potential to impact decision-making in the respective sector [35–38]. Over the last 20 years, this approach has been successfully conducted in many fields, including landscape restoration [39], forestry [40], agriculture [41], urban stream ecology [42], microbial ecology [43], hydrology [44], conservation physiology [45], fish migration [46], recreational fisheries [47], and smart (energy) consumption [48,49]. This integrative approach seeks to incorporate and dialogue with various stakeholders, including practitioners, legislators, and researchers, to refine and distill a set of questions until 100 high-priority questions emerge [35–37].

This research targets three main types of actors: First, we address policymakers and practitioners in public, private, and non-profit organizations as addressing their questions can meet their information needs. Second, funders of research must better understand which broad themes to prioritize. Third, researchers must know which questions policymakers consider most important [36].

This study identified a list of policy-relevant and high-priority questions in the hydropeaking research and management field. We created an online survey distributed globally to individuals and organizations in science, practice, and policy to solicit questions. The initial list of questions was then distilled in a participatory follow-up expert study [36,37], yielding the top 100 research questions for the field of hydropeaking presented in this work. This consensus list of high-priority questions shall inform and guide researchers in focusing their efforts on tackling policy and management needs [50], thereby improving the sustainability of peak-operating hydropower production.

2. Methods

In this study, we identified 100 high-priority questions in the field of hydropeaking research, policy, and management using the Delphi method for expert consensus. The Delphi method is a structured communication approach used to gather and refine the opinions of a group of experts on a specific topic [51,52]. It involves a series of rounds in which the experts provide their opinions, and the results are analyzed

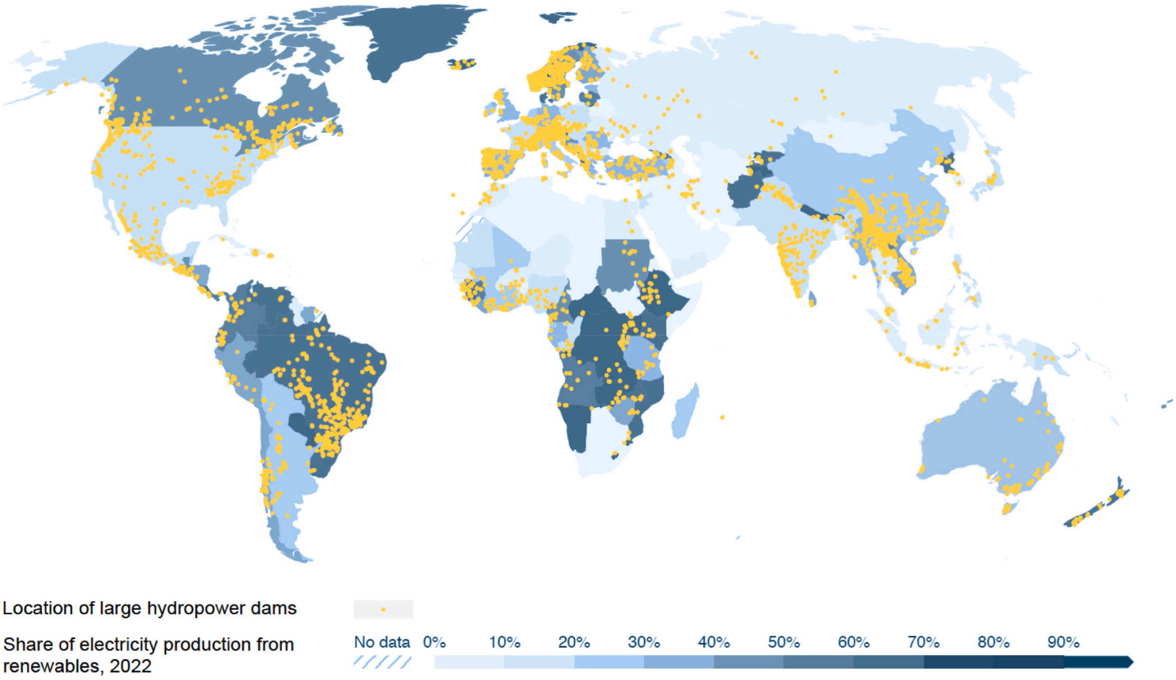

Fig. 1. *Global map of larger dams used for hydroelectricity production and the share of renewable electricity production* per *country. Dams include those from the Global Dam Tracker (GDAT) database* [23] *with 'hydroelectricity' registered as the main purpose or additional use, filtered by a capacity of* >10 MW *and a head of* >*30 m. It can be expected that many large power-generating (storage) dams are operated in peaking mode at least part of the time. A detailed overview of hydropeaking dam distribution, however, is still missing. Renewables include electricity production from hydropower, solar, wind, biomass and waste, geothermal, wave, and tidal sources* [24].

and summarized. The summary is sent back to the experts for review and comments. This process is repeated until a consensus is reached or until the experts' opinions converge [51,52]. The Delphi method is often used to make informed decisions and forecast future developments in fields such as public policy [53], management [52], industry [54], and energy consumption [49].

The implementation of the Delphi expert study was divided into three steps (Fig. 2): (1) we conducted a global call to gather research questions. The solicited questions were then (2) categorized, thematized, and consolidated. Finally, (3) expert rating identified the top 100 questions.

In the first step, we called for questions by inviting experts (i.e., policymakers, hydropower managers, researchers) from various key disciplines or sectors (for example, government, non-governmental organizations (NGOs), industry, academia) and geographic locations (i.e., from all continents where hydropower is used; Fig. 1) to contribute their key questions in the field of hydropeaking [47]. We gathered the questions through an anonymous online survey. The baseline question was: "What are the unanswered research questions in the field of hydropeaking?" [43]. We encouraged participants to list as many as they feel are relevant.

In addition to formulating questions, surveyors were also asked to disclose information about their expertise (topic and years of experience), occupation, and country of work. The questionnaire was available in six different languages (English, Spanish, French, German, Italian, and Portuguese), following the suggestion of Cooke et al. [38].

The call to the online survey was distributed through means of circulating emails, newsletters, professional societies, social media (Twitter and LinkedIn), and key regional informants (for example, hydropower managers). This global distribution was largely based on the contacts and efforts of the Hydropeaking Research Network (HyPeak [55]) and the further solicitation of survey participants to their colleagues and networks. The online survey ran from December 2021 to February 2022.

In the second step, the questions were (i) translated into English (if necessary), (ii) refined and rephrased (if necessary), and (iii) sorted into sub-categories within eight major topics: (a) hydrology, (b) physicochemical properties of water, (c) river morphology and sediment dynamics, (d) ecology and biology, (e) socio-economic topics, (f) energy markets, (g) policy and regulation, (h) management and mitigation measures (Table 1). In addition to the survey outcomes, (iv) the hydropeaking questions posed by Hayes et al. [17] and Alp et al. [55] were integrated into the list. Finally, (v) any duplicate questions were removed due to redundancy.

The third and final step aimed to winnow and refine the questions by conducting formal voting in the form of a Delphi study. We distributed the final list of questions to all survey participants who indicated their willingness to contribute to such a follow-up expert study. Each expert could decide on which and how many topical groups they wanted to join [41]. The experts had to rank each question within a topical group

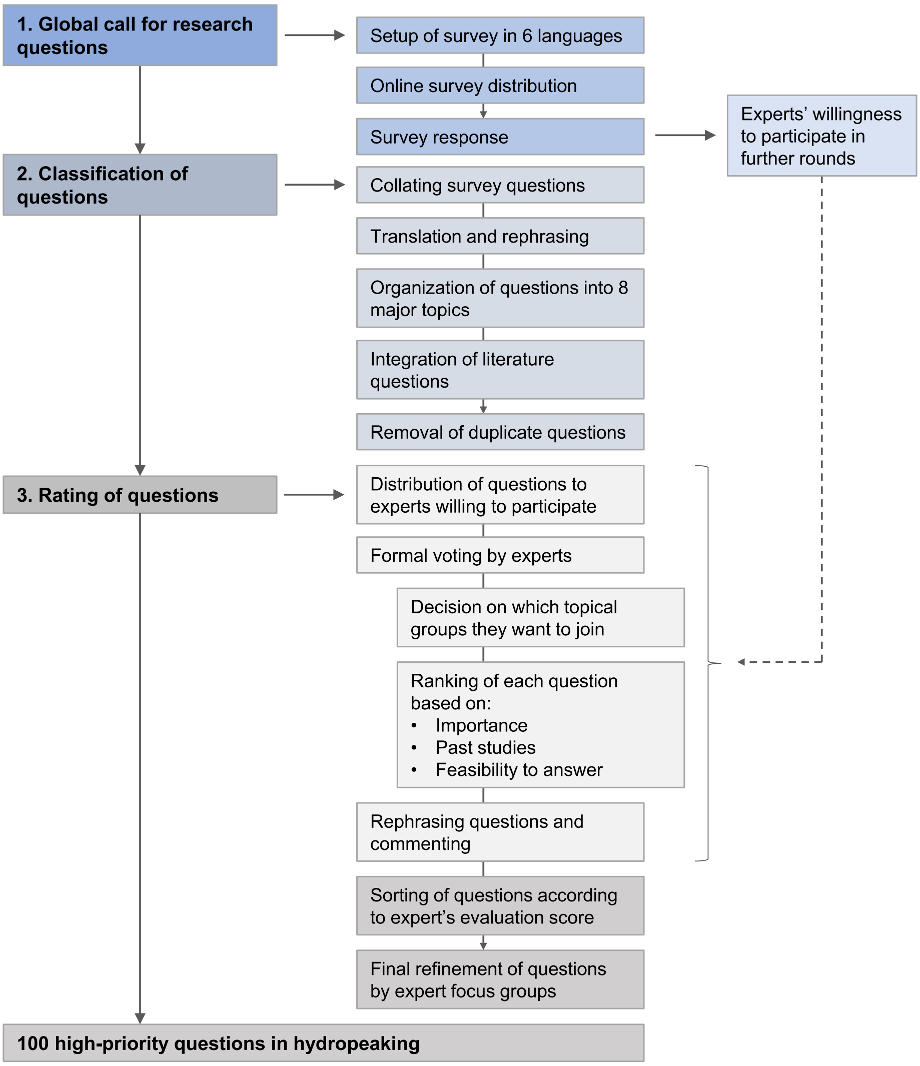

Fig. 2. Schematic flowchart providing an overview of the step-wise implementation of the Delphi method for this study.

Table 1
Identified hydropeaking topics and the total number of questions classified by each topic before and after the rating approach, and the number of experts involved in ranking questions in each topic.

Topic	No. of original questions	No. of questions included in the final list	No. of experts involved in the ranking
Hydrology	50	15	9
Physico-chemical properties of water	19	4	6
River morphology and sediment dynamics	47	13	8
Ecology and biology	140	34	13
Socio-economic topics[a]	28	6	5
Energy markets[a]	27	9	
Policy and regulation	47	8	6
Management and mitigation measures	74	11	8
Total	432	100	29[b]/55[c]

[a] Socio-economic topics and energy market questions were ranked by the same experts.

[b] Number of experts involved in the ranking of questions.

[c] Total count of expertise involvement, including certain experts who joined multiple topics and were thus counted for each.

according to (i) the importance in knowledge gain for hydropeaking management, (ii) how well it has already been studied (i.e., the question should not have already been answered), and (iii) how feasible it is to answer the respective question through a realistic research design of spatial and temporal scope [36]. The ranking scale ranged from 1 to 10, whereby 1 indicates the least and 10 the highest levels of importance, already existing research, or study feasibility. Expert group members were also invited to revise and rephrase questions where they felt relevant or leave comments [37,56].

Essential questions are defined as those questions that, if answered, would have the greatest impact on global hydropeaking research and policy. For each question, we calculated the mean score of the expert's evaluation regarding the three evaluation categories mentioned above, including the percentage of experts that evaluated the question. We then combined the three values per question into one ranking index (1–30) by summing up the means (the values regarding how well the respective question has been studied were re-coded by inverting the order). Furthermore, the percentages of expert participation were combined (0–300). As selection criteria, we used the ranking index to sort the questions in descending order, picking the top 100 but excluding questions with an expert participation score $\leq$150 across the three questions (i.e., importance, how well studied, feasibility). In cases where questions that the experts marked as redundant ended up in the 100 questions list, these were combined into one question by expert focus groups. Then the next question according to the ranking index order was added to have a total number of 100 questions. This process was repeated as often as needed.

The questions were tested against the following further criteria for the identification of properly formulated scientific questions: (i) questions should have a factual answer that is not based on personal opinions or beliefs, (ii) they should be specific rather than covering a general topic area, (iii) they should not be answerable with "it all depends", (iv) unless they are questioning a specific statement, they should not be answerable with a simple "yes" or "no" (for example, not "is the mitigation option X better than Y?"), (v) when related to impact and intervention, they should include a subject, an intervention, and a measurable outcome [36,41,56]. In cases where a question was removed due to one of these criteria, the next question according to the ranking index was selected and added to the final list (as in the previous steps).

This stepwise approach to winnowing and refining gathered questions through a participatory exercise eventually yielded what we consider to be the top 100 research questions of relevance to hydropeaking research and policy.

3. Results

3.1. Round 1 – global call for gathering research questions

In the first round of the Delphi study, the sample included 220 respondents who submitted research questions (out of 2879 survey clicks). Respondents had an average experience of 18.7 years in their field of work and 9.8 years in hydropeaking. The participants had their working base in all continents where hydropower is used. Of the experts who disclosed their primary working areas (n = 212), the majority of participants work in Europe (n = 173), Asia (n = 13), North America (n = 11), Africa (n = 8), South America (n = 5), and Australia and Oceania (n = 2). The seven most prevalent countries represented were Switzerland (n = 43), Italy (n = 26), Austria (n = 24), Germany (n = 17), Spain (n = 16), Portugal (n = 13), and France (n = 11) (Figure S1).

Nearly half of the respondents had a background in research (n = 103), followed by government/authority (n = 37), hydropower management (n = 24), and NGOs (n = 20). Other stakeholders included individuals from the field of consulting (n = 13), energy provision (n = 10), fisheries (n = 9), and others (n = 4) (Figure S1).

In total, 432 unique research questions associated with eight topical areas could be identified (Table 1; Fig. 3). Of the 220 respondents, 48 indicated their willingness to contribute to the follow-up expert study to rate the gathered questions in order to identify the most relevant ones.

3.2. Round 2 – expert rating to identify high-priority questions

In total, 29 experts contributed to the next round of rating the questions (Table 1). The majority of these experts were researchers (n = 24). Some work in the government/authority sector (n = 4) or hydropower management (n = 1). The experts' working locations represent all five continents mentioned above (up to three countries per expert), the largest share work in Europe (Figure S2).

The experts were presented with the topical groups shown in Table 1. They could join as many of these topics as they identified with, resulting in 55 total expert responses (Figure S2).

3.3. One hundred key questions in hydropeaking

The step-wise implementation of the Delphi method identified the top 100 questions in hydropeaking from 432 original questions (Table 1). Fig. 3 provides a graphical representation of this process, showing which original questions were selected, combined, split, or not selected by the experts. We assigned questions to thematic subcategories for grouping irrespective of their association to one of the eight topical categories.

The following sections present the final 100 questions list organized by category. Each category is prefaced with a brief introduction. The order of questions does not reflect a priority as they are sorted according to theme.

3.3.1. Hydrology

From a hydrological perspective, hydropeaking is a phenomenon that has been addressed by considering multiple spatial and temporal scales [57,58]. Time series of river discharge have been analyzed at single gauging stations [59], in a network of gauging stations belonging to the same catchment [60–63], and also at larger regional scales [64,65]. The focus of these studies was mainly the identification of changes in the hydrological regime due to the construction and operation of hydropower infrastructures, and the problem was addressed at temporal scales ranging from minutes to years, showing how the temporal dynamics of hydropeaking flow regimes differ from natural ones [66,67].

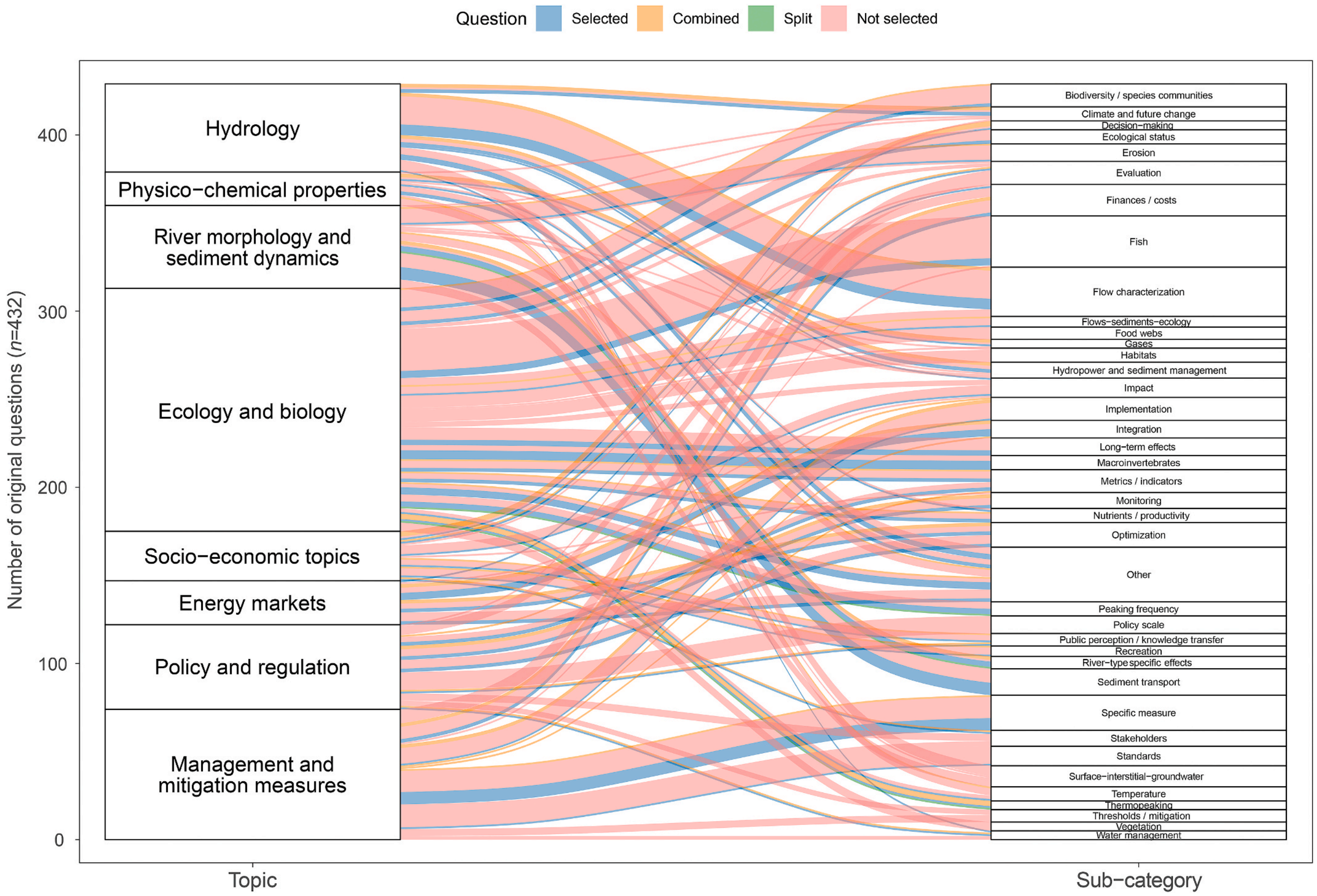

Fig. 3. Alluvial plot showing how the eight topics (on the left) are linked to thematic sub-categories (on the right, sorted alphabetically; all categories with ≤5 questions were added to "Other"). The line colors indicate if the respective original question (n = 432) was selected, combined, split, or not selected for the final 100 questions list.

Catchment-scale hydrological models that aim to reproduce the effect of hydropeaking often use daily time steps and are, therefore, unable to address sub-daily streamflow variability, particularly when the research question focuses on climate change projections and hence long simulation times [68]. Also, coupling energy production and hydropower generation mechanisms with process-based models at multiple spatial and temporal scales remains challenging. However, machine learning methods could contribute to overcoming this limitation [69].

A hydrological approach to studying hydropeaking also requires considering the effects of river stage fluctuations on surface water-groundwater interaction. In this case, several authors have acknowledged the importance of investigations at the local scale [70] and for river reaches [71,72]. When designing and implementing suitable restoration measures, it is necessary to consider the typical spatio-temporal interaction among the different hydrological processes. Further, attenuation and ramping rates influence morphological and ecological impacts within the river system [73].

The following questions demonstrate the complexity of processes linked to water storage and release effects for hydropower generation and the importance these have on the hydrological cycle. Adequate monitoring, modeling, and mitigation will require developing new tools that embrace this multiscale aspect.

1. How does the temporal resolution of streamflow (or river stage) data affect assessments of hydropeaking hydrology?
2. What spatiotemporal variations of flow velocity, water depth, and wetted width can be observed in hydropeaking rivers?
3. How can zero-flow events occurring in-between hydropeaks, when hydropower stations are on hold due to low energy demand or low electricity prices, be adequately measured?
4. How does base flow duration and magnitude between hydropeaks differ from natural flow fluctuations?
5. How does peak flow duration and magnitude in rivers affected by hydropeaking differ from natural flow fluctuations?
6. Which flow quantiles can be used to standardize global assessments of hydropeaking frequency?
7. How can improvements in remote/local sensing techniques, modeling tools, and smart energy grids allow for more dynamic (i.e., real-time) release strategies to minimize hydropeaking impacts while answering energy demand?
8. How do hydropower cascades affect hydropeaking, including the potential amplification of hydropeaking waves at different flow conditions?
9. How does hydropeaking hydrology change over time in relation to energy markets?
10. How does hydropeaking affect natural ice regimes?
11. How do environmental flows affect characteristics of hydropeaking hydrology, such as the rate of change, flow ratio, peak amplitude, or between-peak flow magnitude?
12. How do characteristics of the hydropower station, such as reservoir size and location or operational rules, influence the degree of hydrological alteration?

13. What are the implications of non-stationary hydrological regimes (for example, due to climate change or natural/anthropogenic forcing mechanisms) on hydropeaking hydrology?
14. How do different morphological rehabilitation measures dampen the hydrological effects of flow or river stage fluctuations by impacting flow retention of the hydropeaking wave?
15. How will climate change alter hydropeaked rivers, considering both changes in the management of hydropower systems and the hydrological cycle?

3.3.2. Physico-chemical properties of water

River damming creates lentic ecosystems that affect physical, chemical, and biological processes and characteristics in the downstream reaches [74,75]. Accounting for the sub-daily alterations of physical (for example, thermopeaking, temperature [76–78]) and biochemical (for example, gas supersaturation, water quality [79]) processes and patterns related to hydropeaking adds challenge to their further understanding. It may require multi-parametric and high-frequency field sampling, but also the modeling of biogeochemical processing occurring in the upstream reservoirs and the downstream sections [80] as well as changes in the interaction with the hyporheic zone [81] and the aquifer [82].

Some of the most frequently studied physical alterations associated with hydropeaking are the sharp and intermittent alterations of river thermal regime associated with hydropeaking, so-called thermopeaking [76–78]. The general role of damming and related hydropower operations on river biogeochemistry, including nutrient and carbon cycling, has been studied [83,84]. However, specific studies and analyses of the effects associated with hydropeaking are lacking, although investigations on how hydropeaking affects the dynamics of dissolved gasses have been growing in recent years. Pulg et al. [79] provided evidence of gas (nitrogen) oversaturation (“saturopeaking”), while Calamita et al. [85] shed light on the hydropeaking effects on carbon dioxide fluxes (“carbopeaking”). The effect of river fluctuations on flow exchanges with the aquifer and solute transport has also been investigated at multiple spatial and temporal scales [86,87].

Despite growing attention, the short and long-term consequences of physico-chemical alterations on the downstream river and aquifer ecosystems are still partially overlooked. Currently, the most remarkable knowledge gaps, as indicated by the following questions, refer to the understanding and quantification of biogeochemical alterations at the temporal scales at which hydropeaking occurs.

16. How does hydropeaking affect the water quality of the downstream river sections when released from eutrophic reservoirs?
17. How does hydropeaking (and, if co-occurring, thermopeaking) affect daily and seasonal dynamics of dissolved gasses (for example, oxygen, carbon dioxide, methane)?
18. How does hydropeaking influence the interdependent processes of nutrient cycling and their downstream transport (nutrient spiraling)?
19. To which extent are physical (hydraulic and thermal) hydropeaking-driven alterations more (or less) relevant than chemical (water quality) ones as environmental stressors?

3.3.3. River morphology and sediment dynamics

Hydropeaking operations significantly impact the morpho-dynamic processes of river systems [3]. The rapid oscillations of flow generated by hydropeaking directly interfere with rivers’ natural flow and associated sedimentary regimes, and, in turn, with their ecological functioning [88–90]. The high instability of channel habitats is a main limiting factor for freshwater ecosystem functionality because hydropeaking modifies flow hydraulics, the sedimentary structure of the riverbed, sediment transport, and habitat availability [91–93]. The morphological and sedimentary dynamics of river systems are occasionally affected by the joint effect of reservoir sedimentation and hydropeaking, a combination that may exacerbate sediment deficit and associated effects such as riverbed incision and armoring [94].

Overall, sediments in rivers experience cycles of entrainment, transport, and deposition. Floods are major natural disturbances that, together with anthropogenic impacts, control or modify such cycles [95]. Particle mobility depends on bed structure, and ultimately, they are both strongly influenced by the upstream sediment supply in the system. Therefore, understanding the frequency and magnitude at which water flow exceeds the sediment mobility threshold is fundamental to correctly characterize such processes [96]. Hydropeaking-affected reaches, in particular, where the flow is artificially increased and the upstream supply of sediments has been cut off, frequently experience processes of full or partial bed mobility driven by the entrainment of sediments [97]. This may generate a sedimentary imbalance that can affect various ecological processes (for example, fish spawning, invertebrate refuge). The sediment deficit may be mitigated through the regular release of natural-like floods providing sediments [98] or augmentation of key sediment fractions, improving habitat availability and maintenance [99].

Although a few studies focused on the morphological impacts of hydropeaking, the following questions demonstrate substantial knowledge gaps in the field of morphological and sedimentary processes at various spatial and temporal scales.

20. How are sediment depletion (removal of ecologically valuable gravel) and hydropeaking related to each other?
21. How does hydropeaking affect fine sediment dynamics and related habitat properties?
22. How can the impacts of hydropeaking and the impacts of dams on morphology and sedimentary processes be distinguished?
23. How does hydropeaking affect the riverbed composition in terms of fine sediment content, sorting processes and particle size distribution?
24. How does hydropeaking affect mobility thresholds and sediment transport processes compared to those found in non-regulated rivers?
25. How does hydropeaking affect riverbed stability and bed armoring?
26. What is the role of tributaries in mitigating sediment deficit in hydropeaked rivers?
27. What are short- and long-term morphological consequences of hydropeaking?
28. How does hydropeaking alter morpho-dynamics in different river types?
29. What are the timescales of aquatic habitat (wetted area) persistence during turbine shutdown events in hydropeaked rivers?
30. What are the key hydropeaking flow characteristics (for example, magnitude, frequency, ramping rate) that lead to changes in river morphology and sediment transport?
31. What are – from a morphological perspective – the spatial scales (for example, patch, reach, segment) that are most affected by hydropeaking?
32. What flows and sediments need to be released from dams to maintain or restore the sediment dynamics in hydropeaked rivers?

3.3.4. Ecology and biology

Water flow is a key driver of physical and ecological processes within rivers [100]. Therefore, any change to the natural flow regime will affect aquatic habitats, organism communities, and ecological processes in river systems [101–103]. The rapid and artificial flow fluctuations associated with hydropeaking operations affect riverine biota (fauna and flora) directly and indirectly. Direct effects include organism displacement, involuntary drift, and stranding, often leading to deterioration and death [104–109]. Indirect effects are linked to changes in river hydro-morphology with consequences for habitat quality and availability and include alterations of biochemical processes and biotic interactions [13,110].

The study of ecological and biological impacts of hydropeaking has focused to a large extent on responses of certain life stages of fish and macroinvertebrates [111–114]. Research has recently also been conducted on riverine plants and flow-vegetation relationships [2,108,115]. In contrast, other life stages and organism groups, such as biofilm and microbial communities, crayfish, and bivalves, have received little or no attention [116] despite being important river ecosystem components. The same goes for terrestrial biota that depend upon river ecosystems for their life cycle (for example, birds). Also, hydropeaking effects on the propagation and establishment of non-native species in aquatic and riparian environments are hardly studied.

Moreover, hydropeaking effects on river connectivity, including interactions with other related factors, in its different dimensions (i.e., longitudinal, lateral, vertical, temporal [117]) are largely unknown. The shallow river margins and sediment bars are particularly affected by hydropeaking as artificial flow fluctuations with oscillations between dry and wetted conditions create 'artificial intertidal zones' [118]. These oscillations affect the groundwater table and riparian environments [71,72], as well as the lateral instream habitat connectivity [119,120], including links between aquatic and terrestrial environments. The hyporheic zone, which largely relies on intact vertical connectivity, is important for biochemical and biotic processes [121]. Vertical connectivity in hydropeaked rivers can be affected directly, for example, by the propagation of the hydropeaking wave into the shallow aquifer [122], or indirectly, for example, by altered sediment dynamics and associated clogging processes [91]. The impacts of these hydropeaking-driven connectivity alterations on biota are largely unknown.

To achieve sustainable management of hydropeaking and the conservation of river ecosystems, we must improve understanding of how the interrelations of hydropeaking, thermopeaking, and saturopeaking impact ecological processes in rivers [79,123,124]. This includes identifying the time scales over which biotic communities can adapt to these changes. Additionally, given the range of hydrological variables impacted by hydropeaking, it is crucial to identify which variables are primarily responsible for the negative effects on biological communities [11,13,14]. This information is essential for exploring potential mitigation strategies through direct mitigation measures [17].

Finally, hydropeaking is not the only anthropogenic stressor that rivers face, as they are also frequently affected by various other human-driven impacts, such as channelization [11], eutrophication, pollution, the spread of exotic species or other types of flow modification (for example, water abstraction) [125]. Therefore, in order to ensure the effective conservation and management of riverine ecosystems, it is essential to consider hydropeaking in this multiple-stressor context and examine how the combinations of stressors, as well as their seasonal and geographic variations, will influence the resilience and adaptability of riverine communities [126], particularly in light of climate change.

33. How does hydropeaking affect riparian or gravel bar invertebrate communities?
34. How does hydropeaking affect the nutritional quality of periphyton?
35. What are the effects of hydropeaking on the structure and biomass of algal and microbial communities in the biofilm?
36. How does hydropeaking (and, if co-occurring, thermopeaking) impact river biochemical processes (for example, microbial metabolism, nutrient spiraling) in rivers and/or their receiving water bodies (i.e., lakes, estuaries)?
37. Which role does the duration of baseflow between hydropeaks play in structuring biological communities?
38. To which extent do tolerance, acclimation, or habituation allow aquatic species to live in regularly-occurring hydropeaking conditions?
39. How do the ecological effects of very frequent, low-intensity flow fluctuations ('hydrofibrillation') differ from those of regular, but less frequent high-intensity hydropeaking?
40. To which extent do single high-flow events differ from reoccurring hydropeaks in determining habitat dynamics and biotic community composition?
41. To which extent do the effects of irregular (seasonal) hydropeaking differ from regularly (year-round) occurring hydropeaking in structuring habitat dynamics and biotic communities?
42. What are the most sensitive biological metrics to assess the ecological effects of hydropeaking on the environment?
43. How does hydropeaking affect the riparian habitat and which metrics can we use to measure the impacts?
44. How does hydropeaking affect crustaceans, such as native and invasive crayfish?
45. How does hydropeaking affect bivalves?
46. How does the temperature of the water released during hydropeaking affect riverine flora and fauna in different seasons?
47. How does hydro- and associated thermopeaking affect different life cycle stages of aquatic organisms and their populations?
48. What are the thresholds above and below which thermopeaking causes measurable harm for different life stages of aquatic organisms?
49. How does the interaction of thermopeaking and climate change-related thermal impacts affect different life cycle stages of aquatic organisms?
50. How does hydropeaking affect functional diversity of macroinvertebrates?
51. Through which life-cycle stages does hydropeaking have the greatest impact on macroinvertebrate population structure and dynamics?
52. How does hydropeaking affect aquatic-terrestrial functional links of invertebrates?
53. Which are the ecological effects of hydropeaking on different time-scales and how do they interact?
54. How does hydropeaking affect fish emergence from the gravel substrate?
55. How does hydropeaking alter riverine lateral connectivity and affect functioning shoreline habitats?
56. How do fish relocate (laterally and longitudinally) during hydropeaking and to what spatial extent do hydropeaking effects continue to influence their movement?
57. What are the broader ecological effects of implementing the 'emergence window' approach proposed as a mitigation option (Hayes et al., 2019, Sust. 11(6), 1547) to safeguard fish populations?
58. How does hydropeaking affect riparian and aquatic birds, such as gravel nest builders or waterfowl?
59. Does hydropeaking facilitate invasion of non-native species organisms and, if so, by which mechanisms?
60. Does hydropeaking facilitate out-competition of native species by non-native ones? If so, by which mechanisms?
61. What are the combined ecological effects of cascading peak-operating hydropower plants?
62. What are the combined effects of general (for example, channelization, pollution) and hydropeaking-specific (for example, saturopeaking, thermopeaking) stressors on populations of aquatic biota in hydropeaked rivers?
63. What is the role of river and tributary connectivity in determining the ecological condition of hydropeaked rivers?
64. How will climate-driven changes in the hydrological regime affect ecosystems already impacted by hydropeaking?
65. What role does long-lasting habitat degradation (for example, from a decadal perspective) play in determining ecological community structure of hydropeaked rivers?

66. To what extent does the impact of hydropeaking differ between scales and river types, for example, pertaining to different flow regimes (glacier-melt vs. non-glaciated regimes; temperate, tropical vs. semi-arid), river morphologies and sedimentary structures (straight vs. braided rivers; armored vs. loose (mobile) bed rivers), groundwater influence (for example, hyporheic vs. surface-dominant flows), or biocoenotic regions such as fish regions (headwaters vs. lowland rivers)?

3.3.5. Socio-economic topics

A common framework for categorizing socio-economic effects on the environment is the concept of ecosystem services, which describes the values of healthy and functioning ecosystems for humans [127]. In particular, hydropeaking may lead to socio-economic effects in rivers on provisioning services (for example, fewer raw materials and less water available and, in turn, effects on livelihoods) and cultural services (for example, recreational activities in rivers such as angling and rafting, education, beauty, and landscape) [128,129]. In contrast to their economic impacts on energy markets and hydropower operators, the economic questions here focus on societal externalities, individual's livelihoods, and distributional issues.

On a broader level, many of the public's perceptions and concerns about hydropower in general are also valid for hydropeaking. These include concerns related to increased hazards (for example, soil erosion, flooding, landslides), destruction of changing landscapes, impacts on livelihoods, and unequal distribution of economic benefits [130,131]. Given the potential impact on recreational and livelihood activities, public involvement and consultation may be relevant to decision-making processes about hydropeaking mitigation.

There have been a few previous studies, which have investigated the impact of hydropeaking on specific recreational activities such as rafting and kayaking [132,133], proposed methods to evaluate human safety [134], and estimated the economic value of hydropeaking externalities [135]. However, studies on other socio-economic dimensions are scarce. Thus, open research questions focus on the role of stakeholder engagement and institutions in decision-making about hydropeaking, public awareness and perception of hydropeaking impacts, measurements of hydropeaking impacts on cultural ecosystem services and relevant indicators, and finally, the integration of social components in the management of environmental flows.

67. What respective roles do different stakeholders and institutions play in shaping decision-making about hydropeaking?
68. What risks to the public are associated with hydropeaking?
69. What are the public perceptions of hydropeaking and associated (for example, thermo-, saturo-, carbopeaking) impacts and how can they better be communicated?
70. Given the existing hydropeaking indicators for ecological impacts, what are appropriate indicators for measuring the socio-economic impacts of hydropeaking (for example, other human water uses both consumptive and in-stream)?
71. To what extent does hydropeaking lead to cultural ecosystem services loss?
72. How can environmental and social components be integrated in the management of environmental flows in hydropeaked rivers?

3.3.6. Energy markets

As electricity generation from renewable energy sources constantly grows, storage hydropower systems have gained increasing attention, particularly given their potential to expand electricity storage capacities [136,137]. Storage hydropower provides the needed flexibility to the power system, and pump-storage facilities even allow certain sources of green energy to be balanced with other green energy sources [138]. Thus, hydropeaking events are projected to increase to balance power in a grid that sees intermittent energy sources being further developed [139].

In Europe, for example, the liberalization of the electricity markets led to closer integration of previously separated national power systems. Thus, the energy prices used to control storage hydropower operations are no longer exclusively linked to national supply and demand. Instead, spot and intraday prices are connected to supply and demand on a continental scale [138]. The fluctuations caused by variable renewable energy sources [7] directly influence price fluctuations at the electricity exchanges and, subsequently, peaking operations [138] as storage hydropower operators can benefit from short-term price volatility. This mechanism is summed up by the merit order effect, describing the contribution of (the cheapest currently operating) power installations on the electricity clearing price and volume.

To date, hydropower production constitutes a valuable source of flexible energy production to regional and supra-national grids, balancing the imperative fluctuations of other intermittent energy sources [6,7]. The detailed extent to which hydropower flexibility contributes to the reliability and resiliency of the power grid varies according to the composition of the energy production portfolio in different countries or regions. For example, hydropower flexibility is projected to greatly contribute to energy production in the European Nordic countries [139].

Hydropeaking mitigation measures will affect economic revenue and energy markets by impacting peaking operations [140]. The extent of economic effects on energy markets depends on the measure(s), including the extent of operational restrictions, volume and investment of peak retention basins or diversion hydropower, or morphological improvements [141]. The energy system may entail losses of flexible power generation capacities and volume, effects on carbon emissions in the utility system, or require additional investments in alternative flexibility options due to operational constraints [141]. However, there is a need to better understand the relationship between peaking hydropower-related services (for example, grid stability, flexibility), economic profits, and environmental costs of hydropeaking, including economic costs related to hydropeaking mitigation measures [130,142,143]. The following questions address hydropeaking's current economical-environmental status at different scales.

73. To what degree does the grid stability and the production flexibility of different countries rely on hydropeaking?
74. As electricity markets are changing, what are the implications for hydropeaking in both developed and developing countries?
75. How can hydropower plant turbine operations be optimized to safeguard river ecology while maximizing revenue for the operator?
76. How can current models that link energy demand and production planning be improved?
77. How do hydropeaking mitigation measures affect the flexibility of peak-operating power plants?
78. How would reduced hydropeaking affect energy production and profit for hydropower companies?
79. How much flexibility loss through hydropeaking mitigation is manageable for electricity markets?
80. How can other renewable technologies be used to support flexible energy generation and mitigate hydropeaking effects (for example, demand side management)?
81. What is the relationship between the increase in volatile renewable inputs to the grid and hydropeaking?

3.3.7. Policy and regulation

Policymakers should support ecological hydropeaking practices in light of the UN Decade on Ecological Restoration (2021–2030). A key challenge for decision-makers is balancing increasing renewable energy production, supporting flexibility and grid security, and preserving ecosystem services [144]. In recent years, guidelines [32,145], recommendations [146,147], and evaluation approaches [148] for hydropeaking mitigation have received increasing attention. Although this trend can be considered positive for freshwater ecosystems, few documents are legally binding [149,150]. Some main policy approaches for increasing sustainable hydropeaking include legal requirements, ecosystem-based policy frameworks, and incentives (for example, the EU taxonomy [151] or economic support of measures).

While a few countries have implemented legal requirements to mitigate hydropeaking [144,152], many frameworks lack concrete hydropeaking thresholds, including the EU Water Framework Directive (2000/60/EC). Rather, the Water Framework Directive provides a hybrid approach with multiple levels of control, one level of coordination (the river basin), and a common goal to reach the "good" ecological status or potential. Further, the biodiversity strategy for 2030 and REPowerEU, as part of the European Green Deal [153], including the proposed new nature restoration law [154], will likely strengthen the commitment to restoring the EU's degraded ecosystems. The non-EU country Switzerland has established some of the most specific legal regulations regarding hydropeaking mitigation and thresholds (Swiss Water Protection Act and Water Protection Ordinance). However, partly diverging interests according to the Swiss legislation will need to be fulfilled simultaneously (i.e., ecological impact mitigation according to the Water Protection Act and the Water Protection Ordinance versus increased hydropower production according to the Energy Strategy 2050). In other countries, hydropeaking mitigation is achieved indirectly through, for example, the Fisheries Act or the Impact Assessment Act in Canada [16]. Regardless of the legal framework, hydropeaking mitigation decisions are often made on a case-by-case basis with various environmental regulations and guidelines at different geopolitical levels (for example, international, national, provincial, or local) [152]. For example, operational hydropeaking rules are already included in >450 hydropower licenses in Norway [155], but compliance to reduce ecological harm should be further improved through more defined thresholds [156]. A river-specific approach is pivotal for appropriately considering the local conditions (for example, climate, hydrology, river morphology, species) of the hydropeaked watercourses [148,152] and targeting the specific flow-alteration source in case of multiple hydropower plants in the basin [62]. A key uncertainty is how policy could integrate hydropeaking mitigation into environmental flow assessments more holistically [19,114,120,157].

On the other hand, incentives such as support schemes, feed-in-tariffs, and green power labels can promote sustainable hydropower and hydropeaking mitigation [130]. Sweden and Switzerland, for example, have established a funding mechanism to compensate hydropower companies for production losses or other costs due to mitigation measures. In Switzerland, measures are financed via a tax of 0.1 cents/kWh on consumers' electricity bills following the Swiss Energy Act. In the USA, the Clean Water Act and the Endangered Species Act can support restoration approaches [152]. The pressure pays principle is quite common in Europe, so hydropower owners must pay all mitigation measures themselves (for example, Norway). Mitigation may be done with the support of public agencies, for example, the Water Agency Rhône Mediterranean and Corsica in France, which covers associated costs. Funding for hydropeaking mitigation may also be conducted by the support of eco-labels that promote environmental measures, such as 'Bra Miljöval' in Sweden [158].

Implementing a hydropeaking mitigation strategy into policy and regulation programs requires a clear adaptive ecosystem-based management approach to determine, monitor, and adapt mitigation measures, if necessary [145]. Integrated policies and good governance are needed to balance the environmental (for example, biodiversity) and socio-economic needs (for example, energy production). Furthermore, such an approach can foster iterative learning processes to re-evaluate and implement inputs (for example, more effective measures from research) and outputs (for example, monitoring of implemented mitigation measures) into policy and management actions, regulations, and guidelines, thereby allowing policies to evolve with scientific knowledge and experience from practice [144].

Key questions needing exploration regarding policy and regulation actions include:

82. How can goals for the energy transition be harmonized with the protection of habitats and biodiversity?
83. How can the hydro-flexibility need for energy and grid security be distinguished from the price-optimization (income) of hydropower operators?
84. How can hydropeaking mitigation be more consistently integrated into environmental flows policy?
85. How does hydropeaking life cycle assessment perform compared to alternative technologies such as battery storage, hydrogen, and pressurized air?
86. How can hydropeaking assessment be standardized while still considering local conditions of the watercourse (for example, river morphology, species diversity)?
87. How can hydrological and hydraulic metrics (for example, ramping rates, flow ratio, water stage, peak frequency, and duration) and thresholds be used to update policies, legislations, and guidelines?
88. What is the role of adaptive management in hydropeaking regulation?
89. How can policy and regulations best implement state-of-the-art research results and thus facilitate the learning process for effective hydropeaking mitigation?

3.3.8. *Management and mitigation measures*

It is essential to have science-based frameworks and protocols to minimize the environmental impact of flexible energy production through hydropeaking and identify relevant mitigation measures [159,160]. Hydropeaking mitigation measures can be grouped into two broad categories: (i) direct and (ii) indirect measures [17,18,146]. The first group aims to modify the peak hydrograph directly by releasing environmental flows, modifying operational practices or building constructional features (for example, retention basins, by-pass valves), leading, for example, to lower peak amplitudes or reducing ramping rates. The second group seeks to mitigate adverse hydropeaking effects by adapting the river morphology to improve hydraulic habitat conditions or provide flow-refugia (shelter) for aquatic organisms [17,18,146,161]. Alternative technologies for providing flexible electricity supply other than hydropeaking operations exist and include, for example, pump-storage facilities [162,163], energy storage vehicles [164], inflatable balloons in reservoirs, water pressure chambers, and various types of accumulation batteries [17]. Hydropeaking operations without impacting rivers, for example, by diverting peak flows into lakes or fjords, is also common in some countries [155].

Although hydropeaking is a phenomenon observed worldwide and various measures to mitigate it have been proposed in the literature [17,18,113,152,159], comprehensive implementation of these measures is still lacking (but see Refs. [20–22] for some case studies). Mitigation measures are often disregarded due to their cost, technical complexity, liability concerns, or potential impact on production and flexibility (resulting primarily from operational restrictions). Hydropeaking seems to be less mitigated than other impacts related to hydropower (for example, river continuity for fish) [146,165].

To ensure sustainable hydropeaking operations, it is essential to implement best practice policies (chapter 3.3.7) that combine different hydropeaking mitigation strategies and adopt integrated governance, including legal requirements and incentives that support mitigation and evidence-based adaptive management. For example, the EU taxonomy of sustainable finance [151] is a valuable policy support emphasizing the need for ecologically efficient mitigation of rapid flow changes (including those from hydropeaking). This taxonomy also applies to hydropower projects beyond Europe if the investor is based in the European Union. This fact could increase the application of sustainable, ecosystem-based management and mitigation actions globally [145, 151]. Hydropeaking mitigation strategy should include (i) a pre-mitigation assessment and characterization of the impacts and pressures, (ii) a scenario assessment of the potential effects and acceptability of different mitigation measures (feasibility study), and (iii) a post-mitigation monitoring of the measure effectiveness [32,148,159].

While there have been notable advancements in understanding the ecological effects of hydropeaking based on experimental and case studies (see Moreira et al. [152] and references therein), resulting in targeted recommendations for species- and life-stage-specific mitigation measures [113], examples of sustainable hydropeaking into rivers remain scarce. The issues described above are touched upon in the following questions.

90. What are the most effective ecological measures to mitigate impacts in hydropeaked rivers?
91. How can knowledge and understanding of hydropeaking impacts and mitigation be communicated to decision-makers?
92. What could be the role of hybrid energy systems (for example, pumped-storage hydropower combined with solar), targeted peaking operations and other technologies (for example, battery storage) in hydropeaking mitigation strategies in the expected future?
93. To what extent can increased pump-storage compensate for more operational flow ramping restrictions?
94. What are the best practices to manage sediment regime in hydropeaked rivers?
95. Under which circumstances should operational mitigation measures be prioritized over constructional ones or vice versa?
96. What are the most effective nature-based mitigation measures (for example habitat structures, bedforms, natural ponds) for hydropeaking?
97. What are the economic and system-relevant impacts of applying the life stage-specific mitigation approach (for example, 'emergence window' in Hayes et al., 2019, Sust. 11(6), 1547)?
98. What are the key bottlenecks for faster implementation of relevant hydropeaking mitigation?
99. How should different mitigation measures be prioritized based on cost-benefit assessments?
100. How can we increase the stimulus to apply mitigation measures?

4. Discussion

Flexible hydropower production to balance intermittent electricity (for example, wind and solar) is a key foundation in the low-carbon energy transition and, therefore, constitutes a central aspect in achieving multiple Sustainable Development Goals, such as SDG 7 ('affordable and clean energy') and SDG 13 ('climate action'). However, hydropeaking is also a controversial topic [166], considering that rapid sub-daily flow fluctuations due to turbine operations constitute one of the most significant hydro-ecological impacts on river ecosystems downstream from dams [1,4,113], standing in contradiction to the freshwater biodiversity targets of SDG 15 ('life on land'). Therefore, understanding hydropeaking drivers and their impacts, is critical to determine adequate responses, such as best practice mitigation solutions, protection measures [17,147], and policies.

This study aimed to identify emerging issues in the hydropeaking research and management field, resulting in a list of 100 high-priority questions. These questions, if answered, would have a significant impact on global hydropeaking research and policy by impacting decision-making in the respective sector towards a more holistic and sustainable hydropower management.

4.1. Synthesis of emerging research needs

Hydropeaking has received considerable attention in the literature due to its potential impacts on aquatic ecosystems [2,16,113]. However, the research on hydropeaking has been polarized towards some aspects (for example, stranding of salmonids [152]) while neglecting others, leaving a row of gaps in our knowledge of hydropeaking. Here, we present an ensemble look at the 100 high-priority questions stemming from the Delphi expert study and discuss the broad research needs and interdisciplinary research activities that should be developed in the future.

This study highlights that the ecological effects of hydropeaking on multiple organism groups, including algae and microbial communities, crustaceans, bivalves, and birds, remain largely unexplored. Similarly, the effects of hydropeaking on specific life cycle stages, functional diversity, aquatic-terrestrial links, and specific habitat types, as well as on many key physical processes such as sediment mobility, depletion, and transport, or changes in river substrate structure at multiple temporal and spatial scales, are yet poorly understood. The results also pinpoint the importance of further investigating the socio-economic impacts and energy markets of hydropeaking, as well as implementing mitigation measures at a larger scale and accompanying these through continuous monitoring schemes.

The identified questions underscore the need to increase the knowledge of hydropeaking processes by accounting for the high diversity of biogeographical and hydrological settings of hydropeaked river reaches and the spatial arrangements of hydropower schemes across single and multiple river catchments and scales, including cascade hydropower plants, complex hydraulic schemes, and inter-basin water transfers.

Hydropeaking patterns and impacts are likely subject to change due to ongoing climate trends and socio-economic developments, including a global hydropower boom, intensified water management, sprawling urbanization, and agricultural land use expansion. These drivers often result in further alterations in water flows and sediment transport, deforestation, the input of pollutants and excess nutrients to freshwater systems, and encourage the introduction of invasive species, among others [167]. In this regard, it is imperative to consider the hydropeaking processes in the context of the biosphere changes mentioned above to develop sustainable solutions for the future.

The distribution of final questions across different categories (Table 1) may not accurately reflect the research effort required to address them. For example, the four questions that emerged in the topic 'physico-chemical properties of water' may demand substantial effort to gather environmental data, which are often already available in other environmental fields, but are new regarding hydropeaking studies. Data acquisition and processing will play a key role in addressing most questions but might require new study designs and protocols for novel parameters and a higher spatiotemporal resolution than previously available in hydropeaking studies. Rapid advances in remote and proximal sensing techniques and low-cost environmental sensors [168] can potentially boost research activities in this direction [169].

Many questions can be addressed through computer modeling or 'digital twin' approaches. A digital twin of Earth is defined as "an information system that exposes users to a digital replication of the state and temporal evolution of the Earth system constrained by available observations and the laws of physics" [170]. Traditionally, digital replications of the law of physics for river systems have been based on hydrological and hydraulic models, which provide approximate solutions of mathematical equations that express conservation laws for mass, energy, or momentum. However, anthropogenic effects on water systems [171], as well as biological feedbacks [172,173], are crucial for replicating the behavior of these systems in reality. These effects may even be dominant in comparison to physical processes. Socio-economic driving forces determine water management decisions, for example, those related to diversion, storage, and release of water, and in turn, hydrogeomorphic processes may affect social and economic dynamics [174]. Therefore, new 'digital twin' approaches [170] are needed to describe the complex dynamics of river systems and their linkages with decision-making processes, which are not controlled by the laws of physics. In this regard, artificial intelligence can be used to develop a new generation of socio-hydrological and eco-hydraulic models that consider economic, social (behavioral), and other datasets [175]. An example would be integrating socio-economic drivers with time series data of river and turbine flows, energy markets, and hydro-meteorological conditions, to name a few [176]. Developing such innovative approaches requires a better understanding of physical mechanisms, machine learning algorithms, and their coupling, which can benefit quantitative modeling of water management decision-making.

4.2. A call towards mitigation

By identifying 100 high-priority questions, this study reveals the unknown in the field of hydropeaking research and management. The quest for increased understanding is fundamental to science. We deem it essential that researchers tackle these identified questions to foster even better evidence-based decision support for maintaining socio-ecologically sustainable river functioning [160]. Despite the variety of open questions, it is important to note that there is already a deep understanding of hydropeaking impacts and processes that alter riverine ecosystems [16–18], and there is no doubt that mitigation and restoration efforts targeting hydropeaked rivers must be intensified in the future to meet the UN Sustainable Development Goals.

Many adverse ecological effects are already well-defined in the scientific literature (see chapters 1 and 3.3.4).There is also a portfolio of mitigation measures (see chapter 3.3.8), which has largely remained the same in the last four decades [16]. Nonetheless, good-practice examples for sustainable hydropower projects are still rare [17]. Compared to other anthropogenic impacts, such as pollution and river fragmentation, hydropeaking and its complex hydro-morphological impacts have only recently been included in environmental legislation and management practices – and this only in a limited number of countries [144,152,160]. The general lack of sustainable hydropeaking case studies might be partly due to site-specific conditions often determining mitigation approaches [148,152]. Other reasons for the scarce implementation of measures may be the lack of ecosystem-based governance [144] and the low public awareness of human impacts on river ecosystems and the value of riverine biodiversity, including ecosystem services. Innovative management frameworks [159] and guidelines for consistent prioritization approaches are needed to ensure a common understanding of which measures to choose [146], particularly since peak-operating hydropower is, to date, a key source of flexible, renewable energy of mountainous regions – at least until technological advancements create suitable, environmentally friendly alternatives to hydropeaking.

We see an urgent need for developing conceptual and practical management approaches and cost-benefit tools for predicting the potential effects of mitigation measures [140,148] and their social acceptability across the globe. This should be achieved by implementing evidence-based approaches grounded in existing science. These measures could be continuously updated with new insights, for example, by integrating the answers to the 100 questions or conducting post-measure, long-term monitoring.

4.3. Limitations

Although we intended to reach an audience as broad as possible, we acknowledge that the input received from participants had certain limitations in terms of geography, background, and domains of interest – an issue also inherent to other exercises of the type [43,44,47]. Despite making the global questionnaire available in six widely-spoken languages [38] and widely distributing it through various channels (resulting in ca. 2900 clicks), most of the respondents from both Delphi rounds were based in Europe and came from academia (Figures S1-S2). Also, the proportion of original and final questions across topics revealed a bias towards ecology and biology as well as management (Fig. 3). The data showed a strong positive correlation between the number of participants in the global survey, the initial questions, the experts involved in the ranking, and the final list of questions, respectively, for each of the eight topics (Figure S3). These limitations reflect the current situation in the field, as most published hydropeaking research originates from Europe (Figure S4) and focuses particularly on fish and macroinvertebrate impacts, and partly management [2,152].

International and interdisciplinary efforts, such as those of the HyPeak network [55], may aid in bridging the gaps described above by encouraging global stakeholder exchange. Besides fostering an integrative and interdisciplinary culture, such an expansion to a wider international effort at the science-policy interface will be particularly needed in light of the ongoing hydropower plant construction boom [31], which urgently needs cross-cutting research projects and management outcomes [55].

5. Conclusions

This work presents the outcomes of a multi-round Delphi expert study to identify policy-relevant, high-priority questions in hydropeaking research and management. The final list of 100 questions is a distillation of the original submission consisting of over 400 questions. The presented 100 questions target research objectives that are both achievable and answerable, covering a broad range of topics. The identified 100 high-priority questions, for example, underscore the need to explore diverse organism groups, life cycle stages, and habitat types, as well as the effects on sediment dynamics, energy markets, and mitigation measures. Additionally, considering hydropeaking in the context of climate trends, urbanization, and invasive species is crucial for identifying sustainable solutions. Advancements in remote and proximal sensing and AI-driven socio-hydrological modeling hold promise in addressing these challenges. Integrating multiple disciplines and datasets will be vital to develop holistic and innovative approaches to manage the impacts of hydropeaking effectively. Therefore, the final list of high-priority questions can guide research efforts to provide decision-makers with credible, science-based evidence to improve the sustainable management of peak-operating hydropower facilities.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data (i.e., the questions) are included in the article.

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Appendix A. Supplementary data

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