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River systems under peaked stress

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Abstract

The change in the global energy production mix towards variable renewable energy sources requires efficient utilization of regulated rivers to optimise hydropower operations meet the needs of a changing energy market. However, the flexible operation of hydropower plants causes non-natural, sub-daily fluctuating flows in the receiving water bodies, often referred to as 'hydropeaking'. Drastic changes in sub-daily flow regimes undermine attempts to improve river system health. Environmental decision makers, including permitting authorities and river basin managers facing the intense and increasing pressure on river environments, should consider ecosystem services and biodiversity issues more thoroughly. The need for research innovations in hydropeaking operation design to fulfil both the water and energy security responsibilities of hydropower is highlighted. Our paper outlines optimized hydropeaking design as a future research direction to help researchers, managers, and decision-makers prioritize actions that could enable better integration of river science and energy system planning. The goal of this is to find a balanced hydropower operation strategy.

1. Hydropower within the energy and climate Agenda

Throughout human history, rivers have been at the heart of bustling human civilizations. For centuries, human societies have primarily regulated rivers by building dams to harness their potential benefits. However, the last 100 years have witnessed an unprecedented rate of dam building worldwide (Rosenberg *et al* 2000, Richter and Thomas 2007), causing extensive geomorphological and hydrological changes in the world's major rivers. The hydropower potential of large rivers has already been exploited in most of the developed countries (Wagner *et al* 2015). At the same time, substantial building of new hydropower plants globally is being observed, especially small plants (Couto and Olden 2018).

Hydropower is a cost-effective electricity generation method in countries with suitable natural conditions; it also plays a crucial role in energy security as a domestic energy source (IRENA 2023). However, increasing national and international demands for more flexible management of energy resources in conjunction with ongoing climate change is requiring adaptable hydropower operations. Although beneficial in energy production, hydropower brings forth numerous negative environmental impacts within river corridors (Dynesius and Nilsson 1994). The construction of dams for hydropower purposes has led to significant external effects due to river regulation, resulting in fragmented water bodies. This alteration prevents the natural transport of sediments, leading to siltation upstream and erosion downstream (Baker *et al* 2011, Closs *et al*

2015), affecting the geomorphology, and therefore, habitat creation and food supply in the riverine environment. Consequently, native species such as migratory fish populations (e.g., salmonids) have severely declined due to dam construction (Romakkaniemi *et al* 2011, Quiñones *et al* 2015).

In addition, dam construction has reduced recreational ecosystem services (ES), such as swimming, boating, sport fishing, and whitewater rafting and has had detrimental effects on aesthetic values associated with rivers (Ruokamo *et al* 2024). Although, studies also suggest that some recreational ES can be improved as well when the stabilized water level allows waterborne traffic and similar more lake-style recreational activities (Mattmann *et al* 2016, Botelho *et al* 2017). In general, hydropower reservoirs serve multiple purposes, including flood prevention and supplying water for irrigation, municipalities, and industry (Schultz 2002). However, while they offer ES that can be valuable, there are also concerns about the potential impact on non-market ES. Some studies suggest that losses in these services may outweigh the benefits (Wang *et al* 2010, Intralawan *et al* 2018, Briones-Hidrovo *et al* 2019).

Several hydropower dams were constructed during periods when environmental, cultural, and recreational concerns were not prioritized (Mauer 2020). For instance, the primary purpose for dam-building in Nordic countries was electricity generation, a paramount national interest (Erkinaro *et al* 2011). However, recreational use of watercourses has increased due to increased leisure time, urbanization and increased environmental awareness (Vesterinen *et al* 2010, Facincani Dourado *et al* 2023, Mácová and Kozáková 2023). The greater awareness of the negative impacts of river regulation has led to several dam removal campaigns around the world that aim to restore fish populations and the ecological services they provide (Habel *et al* 2020).

This trend places new challenges for the management of regulated river systems. There are currently policy programs, such as the EU Water Framework Directive (WFD, Directive 2000/60/EC), EU policies on nature/biodiversity and the EU agenda for energy and climate, aiming for a balanced way considering synergies and trade-offs (Kampa 2022). Due to these policy initiatives, hydropower projects typically entail various environmental mitigation requirements. Simultaneously, however, there is the pressure to boost hydropower production to meet increasing energy demands and optimize existing power plants. Consequently, conflicts arise over the alternative uses of river resources (Ruokamo *et al* 2024), and these conflicts are expected to escalate in the future. Hydropower development and operations need to be reconsidered to accommodate the climate targets while simultaneously achieving other Sustainable Development Goals.

More recently attempts to mitigate climate change have led to a global effort toward decarbonizing the energy system through variable renewable energy (VRE) sources such as wind and solar. VRE sources are intermittent by nature and cause integration costs (Joos and Staffell 2018). Integration cost pertains to the developing technologies and tools that allow VRE onto the electricity grid while maintaining grid reliability, security, and efficiency. VRE's cost-efficient integration into energy systems requires flexibility on both the production and consumption side (Cochran *et al* 2012). The utilization of VRE necessitates complementary power resources which the role of hydropower is increasingly highlighted (Hirth 2016). In this context, the value of hydropower flow flexibility in the day-ahead and real-time markets should be included in the environmental flow constraint estimation (Roni *et al* 2023).

Hydropower has been studied in detail with a discipline-specific focus but rarely in a true cross-disciplinary context, one which considers the energy market, economy, society, and environmental needs jointly. Negative externalities caused by the exploitation of hydropower flexibility have received attention for their environmental impacts, especially to flow regimes (Ashraf *et al* 2018) and ecological status within river corridors (Hayes *et al* 2022). Hydropower flexibility results in an unusual and rapid fluctuation in flow for a varied duration in downstream river reaches, also known as hydropeaking. It has been evaluated that river regulation can cause greater changes to river regimes than predicted climate change (Nilsson *et al* 2005). In particular, the impacts of hydropeaking have received increasing attention due to the load balancing demands posed by rising intermittent sources.

2. Hydropeaking rivers: status quo

River regulation causes the homogenization of long-term and seasonal river dynamics (Dynesius and Nilsson 1994, Poff *et al* 2007, Mustonen *et al* 2016) and higher temporal sub-daily flow variations, i.e. hydropeaking (Poff *et al* 1997, Carolli *et al* 2015, Ashraf *et al* 2018). Hydropeaking operations generally involve the release of water based on the energy market demand. The impact of hydropeaking on river flow, ecosystem and sediment downstream of hydropower plants varies considerably, as the operating condition (e.g. limitations in flow variation through ramping rates), the infrastructure (size and location of reservoir and outlets), the environment and the system (hydropeaking flows could be captured by a re-regulating reservoir downstream) of each hydropower plant differs.

In many regional power systems, the role of hydropower is essential as it can be adjusted to rapidly increase or decrease production. This is done

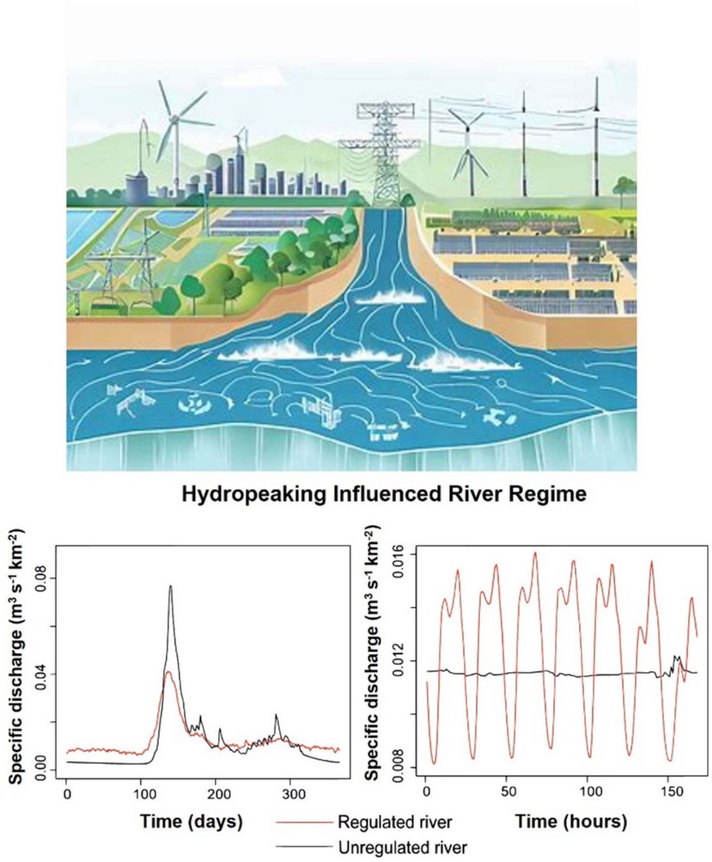

Figure 1. Conceptual figure showing the influences of hydropeaking on the river corridor and example of hydropeaking flow regimes and a systematic understanding sketch. The hydrographs show example flow variation in annual scale (left) and sub-daily scale (right), values are measured flow regimes in natural and hydropeaking influenced river systems in northern climate systems (the river Kemijoki system) with a seasonal spring flood period.

through hydropeaking operations responding to electricity market demands by quickly switching turbines on and off. These start-stop turbine operations occur within minutes and are difficult to predict especially under a deregulated energy market. In the future, countries such as Switzerland and Nordic countries where hydropower constitutes a higher share of electricity production, will likely have to adjust to energy demands by increasing hydropeaking operations (Ashraf *et al* 2018) before more technological advances (such as battery storage) are available in the market. Policies worldwide are being designed and implemented to optimize river regulation from specific to multiple purposes such as specific function of meeting energy demand, or broader functions such as addressing water-energy-food nexus tradeoffs. These policies typically homogenize river flows on a monthly or annual scale. However, more abrupt sub-daily or sub-hourly changes are expected in response to fluctuations in hourly-adjusted electricity markets, as observed in the Nordic region (Haghighi *et al* 2019).

Hydropeaking alters river flow regimes in ways that need to be better understood, as it increasingly shapes river flow and water level conditions (Ashraf *et al* 2018). Hydropeaking completely transforms the hydraulic and hydrological characteristics of a river on an annual, seasonal, daily, and sub-daily time scale (see figure 1). Flow parameters such as peak ratio, amplitude or ramping rates change along a river's course, with marked changes in turbidity (Batalla *et al* 2021, Hayes *et al* 2022). Hydraulic changes alter the entrainment and transport of sediments and, in turn, the sedimentary structure of the riverbed (Batalla *et al* 2021). As sediment transport is fundamental to shaping river habitats, changes become visibly evident at the river reach scale over time. Changes in flow and riverbed habitat affect population dynamics and the diversity of aquatic species (Chen *et al* 2015, Melcher *et al* 2017). Hydropeaking can cause further changes in dissolved gases saturation (Pulg *et al* 2016) or underwater sounds (Lumsdon *et al* 2018). Moreover, hydropeaking can lead to variations in water temperature, a phenomenon referred to as thermopeaking, can impact aquatic fauna in terms of their migration, reproduction, development, and overall survival (Auer *et al* 2023, Mameri *et al* 2023). The main biotic response variables used to quantify the effects of hydropeaking are organism drift (involuntary downstream displacement) and stranding. Indirect effects include reduced food availability, decreased growth rates, and a reduction in reproduction success and fitness. In time, these adverse effects lead to altered biotic community structures and changes in species composition in rivers subjected to hydropeaking (Chen *et al* 2015, Smokorowski 2022). River flow regime alteration is recognized as a key threat to many endangered species and the usability of ES that rivers provide (Bunn and Arthington 2002, Russi *et al* 2012, Fanaian *et al* 2015, Neeson *et al* 2015). At the same time, awareness of non-market ES provided by rivers has been increasing (Fanaian *et al* 2015, Winemiller *et al* 2016, Carolli *et al* 2017, Opperman *et al* 2023). This rise in attention can be attributed to the fact that freshwater biodiversity has declined at an alarming rate (Dudgeon *et al* 2006).

The heavily altered state of many hydropeaked rivers calls for the timely implementation of effective measures to counteract many of the above-described environmental effects. Few studies have looked at how hydropeaking affects the diversity of bio-physical processes in rivers (Batalla *et al* 2021). Each hydropower and its hydropeaking operations are site-specific, making generalisations difficult. Phenomenon of hydropeaking being globally widespread and hydropower mitigation measures developed, are yet to be transferred to guidelines (Hayes *et al* 2023). Investigating the cumulative effects of hydropeaking is crucial for comprehending the resilience of biodiversity and non-market ES within the river corridor.

3. Research priorities: hydropeaking management

Hydropower, as a method of power generation with potentially low carbon emission, has long been a reliable and environmentally friendly method of producing electricity. In recent times, as hydropeaking has emerged as a growing environmental concern and societal demands for river usage have evolved, the emphasis has shifted from simply meeting human needs towards establishing criteria for hydropower sustainability (Hydropower Sustainability Secretariat 2021). These criteria aim to promote healthy ecosystems, prosperous communities, resilient infrastructure, and good governance. In addition, transitioning to equitable and sustainable energy policies also requires that affected social groups' experiences and values be considered in decision-making processes.

Emphasizing sustainability in hydropower especially regarding the challenge of hydropeaking requires identification of less harmful hydropower operation methods. To achieve a balanced energy future, hydropower operations must be re-envisioned in a way that benefits people without harming the planet. Modern environmental standards must be integrated into these operations to protect human and ecological health. Hydropeaking and its mitigation have been on research focus for many years, and various operational (e.g. reduction of downstream ramping) and structural (e.g. downstream pondage) measures have been tested and suggested. However, the current state of practices in global hydropower has not adequately addressed the impacts of hydropeaking on biodiversity or the ES of regulated rivers. As net-zero emission targets progress, hydropower will play a pivotal role mainly due to its flexibility. Hence, there must be a shift towards an ecologically sustainable hydropower approach that could involve evaluation of hydropeaking, mitigation of its impacts, and a valuation of rivers' environmental contributions beyond their ecosystem value.

However, research in this area is lacking and current studies exploring the trade-offs between hydropower operations and the loss of ES are limited (Han *et al* 2008, Kataria 2009, Intralawan *et al* 2018, Venus and Sauer 2022, Ruokamo *et al* 2024). The optimization of hydropower has traditionally focused on ecohydraulics and economics, neglecting ecological and social values. Therefore, an understanding of the relationship between river ecosystem processes and the provision of ES remains obscure, especially from the hydropeaking point of view.

Climate mitigation benefits of balancing energy by means of hydropower may be offset by the long-term local losses due to the socio-ecological damages of hydropeaking. For example, within small hydropower plants, the losses for ES can outweigh the benefits of hydropeaking, due to the balancing intermittencies of variable energy sources. In areas with pristine river conditions, ecosystem resilience and cultural ecosystem value might be substantially higher than hydropower potential. Furthermore, hydropower-induced flow variations can also cause direct consequences to the physical environment such as bank and bed erosion, creating monetary losses through a need for protection actions. Taking steps to address this oversight is crucial to achieving a sustainable hydropower future, which will truly be achieved only through a comprehensive approach respecting all stakeholders.

A broader perspective needs to be adopted for managing rivers and their role in the energy market. The analysis should cover the whole energy system and changes in it, both regionally and globally. It should encompass all aspects of ES and recognize new pressures and drivers stemming from energy market change in our river systems (Ruokamo *et al* 2024). Policy and management options should more effectively consider hydropeaking and local river corridor properties in river regulation. From a regulated river operation and management perspective, a hydropeaking design that optimizes ES and hydropeaking operation jointly, should be considered. This hydropeaking design, which would consider the special local and river corridor needs, energy market needs, and social needs can maximize benefits and help maintain energy production while maintaining healthy river systems (Virk *et al* 2024). Restrictions on hydropower flexibility should be set in

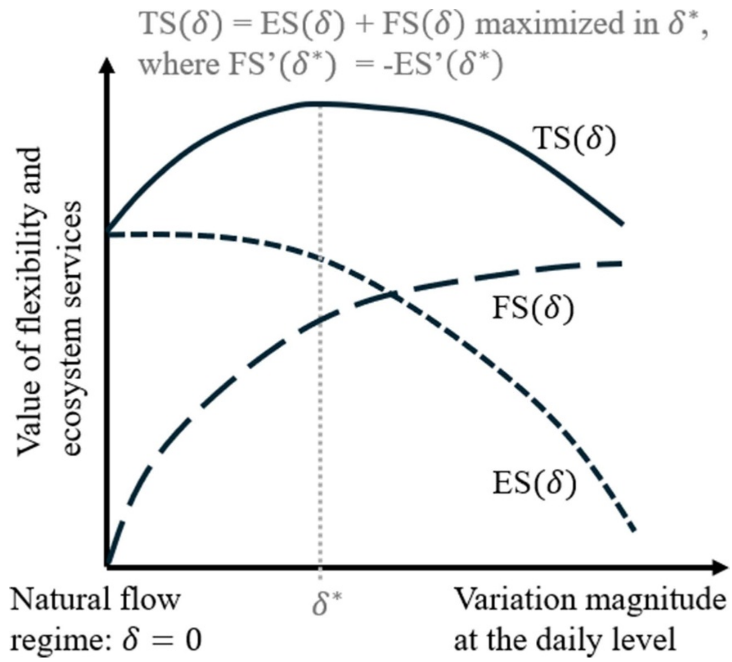

Figure 2. Optimized design for river-specific hydropeaking regulation. For the maximization of total service value (TS), flow variation (δ) can be increased until the marginal change in flexibility services (FS′) equals the marginal loss in ecosystem services (−ES′).

stages and communicated to system planners, stakeholders and investors.

Avoiding hydropeaking entirely is difficult and may not always be the best solution; however, it can be optimized to ensure that the benefits of hydropower generation flexibility are balanced against its environmental effects of flow variation. Figure 2 describes the optimized hydropeaking, showing its viability for avoiding severe hydropeaking effects through the use of future VRE systems. Given values of hydropower flexibility services (FS) and river ES as a function of hydropower flow variation magnitude δ, the regulator should set δ^* as the optimal flow variation level, where the total value of flexibility and ecosystem services (TS) is maximized. While exact quantification of functions FS and ES remains elusive, the concept illustrated in figure 2 underscores the importance of investigating the impacts of tighter environmental flow constraints on hydropower flexibility (see e.g. Niu and Insley 2016, Huuki *et al* 2022) and ES' value (Ruokamo *et al* 2024). Juutinen *et al* (2024) present a Nordic case study demonstrating the feasibility of conducting cost-benefit analyses on mitigating hydropeaking's effects on power system costs and river ecosystem service benefits, suggesting that environmental flow policies can be socially desirable. However, global electricity markets currently lack comprehensive data for holistic analyses, and monetary estimates for enhanced ES resulting from stricter flow ramping constraints are unavailable. Nevertheless, this Nordic example highlights the need for future research efforts in this area to provide essential data for greater sustainability in water and power systems.

4. Prospects and conclusion

Current global trends in hydropower building and operation represent a major risk to river ecosystems and hamper the other desired usage of river corridors. Hydropeaking as a response to the market's operational needs in electricity system balancing can have consequences for river resilience globally if new management approaches and demands are not taken into consideration. Other flexibility measures such as energy storage, demand-side management and sector coupling, will also need to be considered when balancing the expanding share of VRE with increased power demand. Policy makers and river managers should consider sustainable hydropeaking design and operation in regulated river systems that supports river-specific, often contradictory, needs, by reconciling them through an optimization process, such as the one presented here. Optimized design thinking will incorporate an ES approach with the more exact demands of environmental objectives for the renewal of environmental permits of hydropower operators.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

H M contributed Conceptualization, Writing, review & editing, Funding acquisition, Project administration; H H contributed Conceptualization, Writing, review & editing; F B A contributed Conceptualization, Writing, review & editing; E R P contributed Writing, review & editing; S H contributed Writing, review & editing; E R contributed Writing, review & editing; S K contributed Writing, review & editing; R A contributed Writing, review & editing; M K S contributed Writing, review & editing, Funding acquisition, Project administration; E P contributed Writing, review & editing, Z T V contributed Writing, review & editing, A T H contributed Writing, review & editing and A J contributed Conceptualization, Writing, review & editing, Funding acquisition, Project administration.

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