Hydropeaking: Processes, Effects, and Mitigation*

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Glossary

Flexibility (of the power system) The extent to which a power system can modify electricity production or consumption in response to expected or unexpected variability.
Hydraulic stress The measure of the internal force per unit area acting on liquids. In hydropeaked rivers, flow ramping leads to an increase of hydraulic stress for aquatic organisms, often facilitating involuntary downstream displacement (drift) or encouraging them to colonize shoreline areas in the ramping zone that will later fall dry, leading to stranding if organisms are not capable to follow receding water levels.
Hydropeak diversion power plant A hydropower plant that aims to prevent artificial flow fluctuations from occurring in the residual flow stretch created by the construction of a diversion weir.
Hydropeaking The discontinuous release of turbined water due to fluctuations of energy demand. Synonyms include *flow ramping*, *rapid flow fluctuations* or *artificial (sub-)daily flow alterations*.
Pumped-storage power plant Storage power plant which, in addition to turbines, also has electric pumps that enable energy storage by pumping up water to a higher reservoir for later hydropower use.
Ramping zone River area that is exposed to periodic wetting and drying due to fluctuations in water level caused by hydropeaking.
Re-regulation or compensation basin An artificial reservoir below the hydropower plant that retains turbine outflows to reduce hydropeaking intensity in the downstream river section.
River morphology The morphology of a river refers to the patterns and changes in river channel size, shape and bed material over time. It depends on the composition and erodibility of the bed and banks, the availability of sediment, the transport rates in relation to flow intensity, and riparian vegetation. Human activities such as hydropower affect river morphology by altering one or more of these elements and processes, and the equilibrium between them.

Run-of-river hydropower plant Hydroelectric power plant with limited water storage capacity where water is released at roughly the same rate as the natural flow of the river.
Sediment transport The movement and transfer of solid particles (from clay and silt to sand, gravels, and boulders) reacting to the shear forces exerted by a fluid (i.e., water) on the earth's surface, in particular regarding particle mobilized from the erosion areas (catchment's headwaters, river bed, slopes, landslides, etc.) through the fluvial network until distal deposition zones (deltas, estuaries, coasts).
Storage hydropower plant Hydroelectric power plant that stores water in a reservoir and converts the energy of the water into electricity when needed.

Introduction

The energy production scheme inducing 'hydropeaking' was first described in the 1930s in Europe (Vibert, 1939), and is now found throughout the world. Hydropeaking operations are defined as rapid and frequent changes in river flow to optimize hydropower operation (Widén et al., 2021). This rapid operation mode is closely linked to energy markets, which can exhibit quick shifts between production and demand, even changing at sub-daily scales. Fluctuations in energy availability and demand, therefore, directly translate into changes in turbine outflows to ensure grid stability, while generating highest profits (Olivares et al., 2021).

Hydropeaking comes with environmental costs, causing high variability of river flows on a daily or sub-daily basis in the receiving waterbodies. Hence, hydropeaking operations transform a river's hydrological signature and modify morpho-sedimentary dynamics, typically altering the downstream river ecosystem—to an extent that hydropeaking is regarded as one of the most significant impacts downstream of hydropower plants (Hayes et al., 2019).

The ecological effects of hydropeaking have been examined in a growing body of literature, and mitigation options, including dam operational changes and structural arrangements, are considered. This chapter builds upon the current knowledge to provide an overview of hydropeaking processes, effects, and mitigation. In particular, it aims to illustrate how the drivers of peaking-power production and the associated pressures are linked to river ecosystem structure, function and integrity, with a focus on hydro-ecological relationships. Finally, the chapter seeks to provide a process-based overview of mitigation measures from a river- and energy-grid-specific perspective (Fig. 1).

Drivers and pressures of hydropeaking: From a rising demand for renewables to artificial flow fluctuations

Pressing issues such as climate change, fossil fuel resources depletion and decommissioning of nuclear power plants call for an energy transition towards a low-carbon economy. Within this context, hydropower construction is on the rise (Zarfl et al., 2015). Indeed, hydropower is the only system that currently exists to store energy effectively, making up 99% of the global electricity storage capacity (World Energy Council, 2016). Also, hydropower is considered a mature technology that contributes to climate change mitigation by constituting a fundamental building block of today's energy systems. The last decade saw a sharp rise in renewable energy production, with wind and solar sources being increasingly developed (Berga, 2016). Energy production through wind and solar technologies is, however, very variable, but combined with storage hydropower, it can balance out irregularity in the system and supply peak load. These renewable energy sources complement each other well, particularly considering that hydropower from large reservoirs is to date the only reliable method of flexibly producing electricity—besides fossil fuels (Fig. 2).

At the hydropower facility, hydropeaking operations respond to market demands by quickly turning their turbines on (start of production) and off (stop of production). Start-stop operations can occur within minutes and they are difficult to predict in today's de-regulated energy market. In the future, hydropower production will have to increasingly buffer the inevitable energy grid

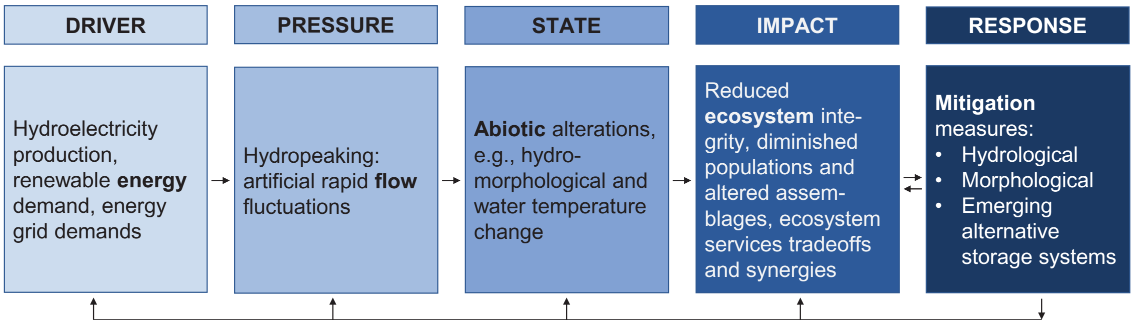

Fig. 1 A conceptual Driver-Pressure-State-Impact-Response (DPSIR) framework for hydropeaking research and management showing causal links and feedback loops.

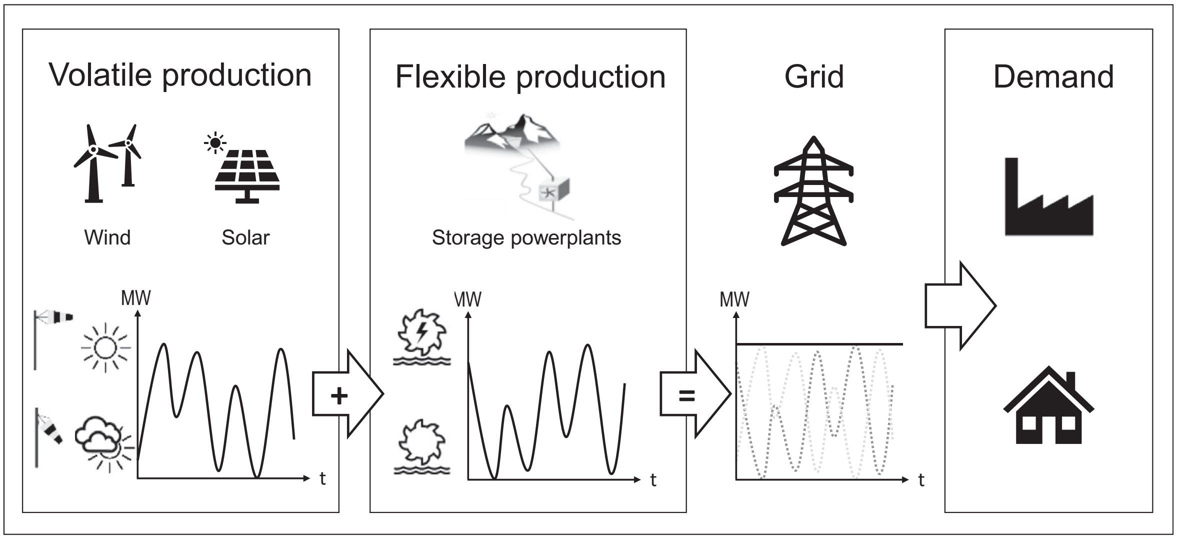

Fig. 2 Hydropeaking power production plays a key role in energy systems with increasing shares of renewables. Due to its flexibility, storage hydropower plants (and other flexible sources) can buffer volatile or intermittent energy sources such as wind and solar, thereby ensuring grid stability and security of supply—a systematic sketch.

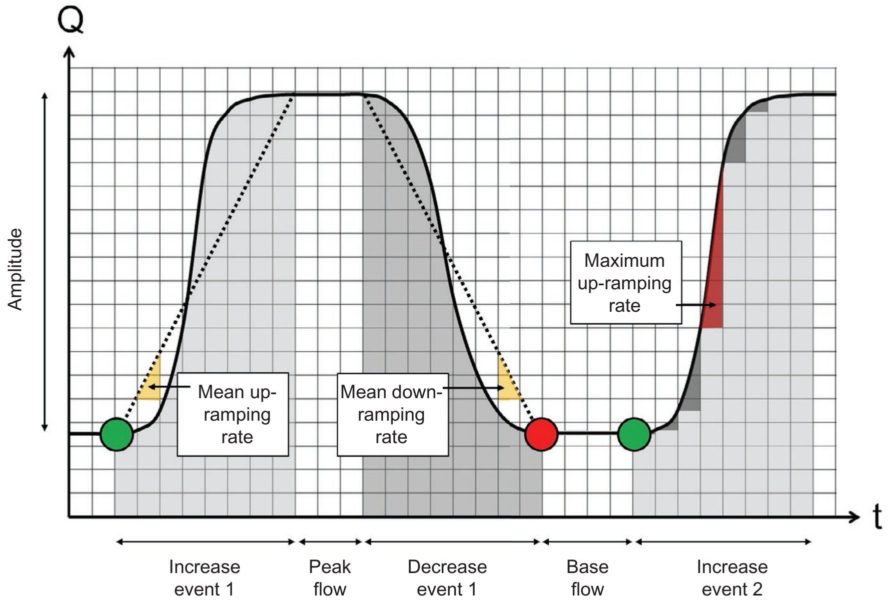

Fig. 3 A scheme of a hydropeaking hydrograph, linking operation start (green circle) and stop (red circle) to the flow regime components: peak amplitude, mean and maximum rate of change during up- and down-ramping, and peak flow or baseflow duration. The frequency and timing of hydropeaks (not illustrated here) describe how often and when (season, time of day) such flow events occur in a river. Modified after Greimel F, Zeiringer B, Höller N, Grün B, Godina R and Schmutz S (2016) A method to detect and characterize sub-daily flow fluctuations. *Hydrological Processes* **30**: 2063–2078. doi: 10.1002/hyp.10773.

fluctuations caused by intermittent renewable energy sources such as wind or solar. In essence, this current and future key function of the hydropower industry is linked to its capability of running hydropower turbines under peak-load conditions and shutting them off during phases of low electricity demand, possibly increasing hydropeaking events (Fig. 3). Indeed, such production schemes not only answer well to market demands but also constitute the backbone of the electricity production of mountainous countries such as Switzerland, Austria, Norway, and Sweden.

In addition to storage hydropower plants, also run-of-river hydropower plants may run a hydropeaking scheme, albeit at lower ranges between minimum and maximum production. A special sub-category of peak-operating hydropower plants are pumped-storage facilities that pump water to reservoirs at higher elevations during periods of low energy demand or costs. Once the demand rises again, the pumped water is released and used to run the hydropower turbines (McManamay et al., 2016; Greimel et al., 2016). Moreover, other human activities can also cause hydropeaking-like conditions, e.g., manipulating gate structures, discharging effluents of wastewater treatment plants, or withdrawing river water for agricultural irrigation.

Hydropeaking hydrology principles

The hydrology of hydropeaked rivers differs from natural river hydrology in two distinct ways. Firstly, reservoirs store water (i.e., incoming river flow) to release it later when needed. Depending on their size, they can either cut off flood peaks (smaller reservoirs) or completely eliminate small and large floods (larger reservoirs). Such flow regulation results also in a homogenization or even total inversion of the seasonal flow regime downstream from the dam (Fig. 4A). Secondly, hydropeaking turbine operations, triggered by peaks in energy demand, result in rapid and often sudden flow changes which are not typical in natural river systems. Such operation schemes entail unnatural flood events in the downstream river section during peak-flow operation. During the shutdown, no or only little water remains in the river (Widén et al., 2021). In between these two flow scenarios, river levels rise (up-ramping) and drop (down-ramping) fast, thereby increasing the rate of change between flows of certain magnitudes (Figs. 3 and 4B–C).

These hydropeaks can be distinguished from natural flow fluctuation events by different intensity parameters such as the five flow regime components commonly used to describe river flows on various temporal scales (Poff et al., 1997). These flow regime components are flow amplitude or ratio, rate of change (also called ramping rate), peak frequency, event duration, and timing. For example, hydropeaking waves exhibit much faster ramping rates than flood waves occurring from rainfall or snow-glacier melt. Similarly, on a daily basis, hydropeaks also entail a higher baseflow: peak flow ratio, peak amplitude, and a shorter peak flow duration than natural flow fluctuation events. Moreover, the different stages of a hydropeaking wave—up-ramping, peak flow, down-ramping—are directly linked to the hydropower operational mode (Fig. 3).

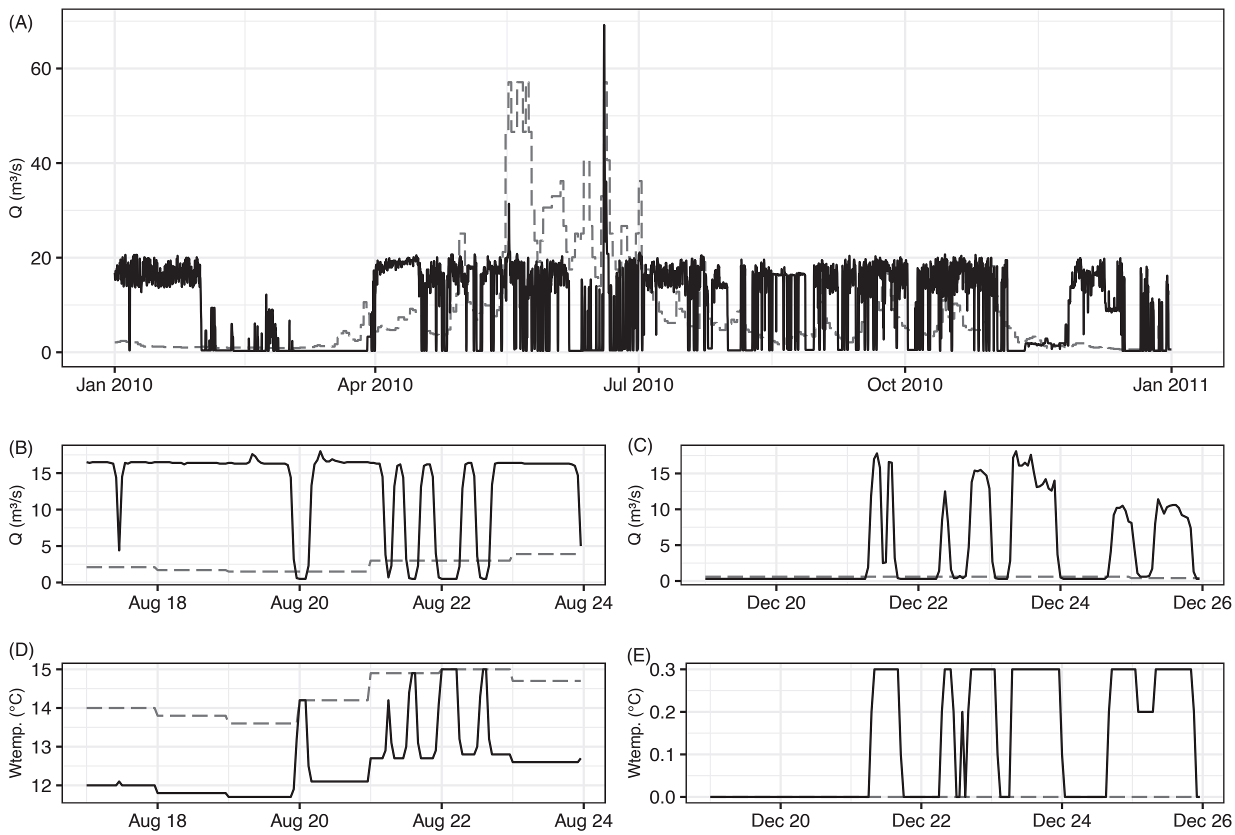

Fig. 4 Contrasting hydropeaking discharge (black solid line) in the Lundesokna River, Norway, with the modelled natural regime (grey dashed line). The panels show differences (A) in annual river flows, weekly river flows (B) in summer and (C) in winter, and weekly water temperatures (D) in summer and (E) in winter. Data resolution: 1 h. Data source: Casas-Mulet R, Saltveit SJ and Alfredsen KT (2016) Hydrological and thermal effects of hydropeaking on early life stages of salmonids: A modelling approach for implementing mitigation strategies. *Science of the Total Environment* **573**: 1660–1672. doi: 10.1016/J. SCITOTENV.2016.09.208.

Effects of hydropeaking

Hydrological regime alterations

Hydropeaking completely transforms the hydrological characteristics of a river on an annual, seasonal (Fig. 4A), daily and sub-daily time scale (Fig. 4B and C). In Europe's mountain rivers, for example, hydropeaking is most pronounced during winter when high peaks of energy demand—resulting in high-intensity hydropeaking—occur during the low flow period when runoff is held back in the form of snow and ice cover. Daily fluctuations of such magnitude only occur rarely and at specific times in free-flowing rivers, and with smoother ramping rates. Regarding peak frequency, glacier-influenced rivers can experience around 100 days per year with significant melt-events; but in hydropeaked rivers, peaks can occur even more frequently, for example, more than 300 days per year in Alpine rivers of Austria (Greimel et al., 2016), although this number can be quite variable—depending on the region, river, or season. In California rivers, for instance, more peaking generally occurs during the dry season than during the wet season. Also, drought years feature increased hydropeaking frequencies over non-drought years (Li and Pasternack, 2021).

Overall, such daily or sub-daily patterns of rapid flow fluctuations are typical of many storage hydropower plants and run-of-river facilities. In addition to characterizing hydropeaking stretches through analyses of single gauges, it shall be noted that flow parameters such as peak ratio, amplitude or ramping rates change along a river's course, underlining the necessity to also incorporate longitudinal viewpoints into more holistic assessments. Due to water retention effects, flow parameters such as peaking intensity usually reduce in the downstream direction. Often, the first few kilometers downstream from the turbine outlets feature the highest hydropeaking intensities. However, the peaks can often still be measured up to 40 km or further downstream of the tailrace (Moog, 1993).

Thermopeaking: Water temperature changes due to hydropeaking

Artificial reservoirs exhibit seasonally different temperatures and tend to form distinct thermal layers during warm and cold weather at the surface, through the water column, and at the bottom. Under such conditions, the release of hypolimnetic (i.e., bottom-layer) water from stratified reservoirs can lead to abrupt sub-daily changes in water temperature in the receiving water body. The pattern of these temperature changes, called 'thermopeaking', is closely linked to hydropeaking (Zolezzi et al., 2011). In temperate regions, these thermal waves lead to a sharp decrease in the stream temperature in summer—cold thermopeaking (Fig. 4D)—and to an increase in winter—warm thermopeaking (Fig. 4E). Similar to hydropeaking waves, the magnitude of temperature changes decreases with the distance from the turbine outlet (Vanzo et al., 2016a) and often there is a decoupling of hydrological and temperature waves (Toffolon et al., 2010; Zolezzi et al., 2011; Fig. 4B–E).

Geomorphological alterations

It is known that changes in sediment transport and deposition alter fundamental characteristics of the streambeds over long time scales and that those changes can alter flow hydraulic conditions, which in turn enable feedback processes that may be critical in hydropeaked rivers (e.g., regarding marked changes in turbidity). Hydraulic changes alter the sedimentary structure and processes acting on the river bed; these include mobility and transport (Vericat et al., 2020), particle entrainment (López et al., 2020), and fine sediment deposition, infiltration (clogging) or porosity (Casas-Mulet et al., 2018; Hauer et al., 2019). Streambed morphology can have a key role in buffering the ecological effects of hydropeaking. Also, considering that sediment transport is fundamental in shaping river habitat, preserving morpho-sedimentary dynamics may aid in reducing undesirable effects derived from peak-energy production (Batalla et al., 2021).

In hydropeaked rivers, changes over time become particularly evident at the river reach scale, and morphological conditions entail direct ecological consequences. For example, as sediment size and bed topography influence the movement of water through the river bed, any changes related therewith entail implications for the delivery of oxygen to fish eggs and embryos that develop within the subsurface zone (Batalla et al., 2021). Overall, braided reaches are considered rather resilient to hydropeaking as they offer the highest habitat diversity and very limited base-to-peak variation, thereby entailing only low drift rates of macroinvertebrates. Alternate bars, in contrast, are extremely sensitive environments to drift, but they do offer safer regions from stranding (see section "Ecological impacts linked to flow alterations" for more information). In turn, transitional morphologies between single-thread and multi-thread offer the best eco-hydraulic trade-offs, according to hydraulic modelling approaches (Casas-Mulet et al., 2015a; Vanzo et al., 2016b). Sedimentary structure at the patch scale is critical to sustain species micro-habitats and it is also affected by hydropeaking (Table 1). However, the exact mechanistic causes of all these bio-physical alterations and feedback mechanisms remain unclear; hence more research is still needed in this direction, also as a sound base to support rehabilitation programs.

Other abiotic changes due to hydropeaking

Hydropeaking can further entail changes in dissolved gases saturation ('saturopeaking'; Pulg et al., 2016) or underwater sounds ('soundpeaking'; Lumsdon et al., 2018). Saturopeaking refers to fluctuations of gas saturation that follows the pattern of hydropeaking waves, and soundpeaking describes temporal variations in the sound frequency composition; the reader is referred to Moreira et al. (2019) for a concise overview on these topics. Recently, also 'carbopeaking' has been described as CO_2 leaks downstream of hydroelectric reservoirs (Calamita et al., 2021).

Table 1 Examples of abiotic river attributes affected by continuous hydropeaking.

Attributes	*Effect*	*Causal processes*	*Scale*
Water turbidity	Increase	River bed resuspension, bank erosion	River reach, i.e., 10^2 m
Bed armor	Increase	Selective particle entrainment, fine sediment depletion (winnowing)	Particle and patch, i.e., 10^{-3}–10^{-1} m
Bed roughness	Increase	Selective particle entrainment	Patch to reach, i.e., 10^{-1}–10^2 m
Bank stability	Decrease	Unsteady wave heights, pore pressure variation, peak flow duration, discharge amplitude	Reach, i.e., 10^2 m
Water surface width	Highly variable	Sudden and repeated flow increases and decreases	Patch to reach, i.e., 10^{-1}–10^2 m

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Ecological impacts

Hydropeaking is considered a key stressor in river ecosystems, altering habitat conditions, local food webs, and a suite of ecological processes. To illustrate flow-ecology relationships in hydropeaked rivers, the following section describes specific processes linked to separate flow parameters and phases of a hydropeak as described in section "Hydropeaking hydrology principles". Indeed, river biota shows distinct responses to those different flow alterations (Fig. 3; Table 2), which are also directly linked to morphological conditions and other physical changes (sections "Geomorphological alterations" and "Other abiotic changes due to hydropeaking").

The main biotic response variables used to quantify effects of hydropeaking are organism drift (involuntary downstream displacement) and stranding. Indirect effects include reduced food availability, decreased growth rates, as well as reduction in reproduction success and fitness. In time, these adverse effects lead to altered biotic community structures and changes in species composition in rivers subject to hydropeaking (Schmutz et al., 2015; Smokorowski, 2021).

Ecological impacts linked to flow alterations

Peak amplitude and base: peak flow ratio. Hydropeaked rivers experience fluctuating hydraulic forces. An increase in discharge leads to an increase in flow velocity and bottom shear stress. To cope with such quickly changing conditions, aquatic organisms such as macroinvertebrates and fish must invest significant amounts of energy to avoid detachment from the substrate or downstream displacement. Field and experimental studies have shown that this so-called involuntary or catastrophic drift of organisms is strongly linked to the amplitude and the flow maximum of hydropeaking events, which are key determinants of river hydraulics. The tolerance towards hydraulic stress differs between species and life cycle stages, which may exhibit varying sensitivity towards flow as well as different behavioral and physical adaptations to flowing water (Hayes et al., 2019; Smokorowski, 2021). Nevertheless, an increase in flow-related parameters, such as water depth and flow velocity, leads to increased physical stress acting on the animals and hampers vital processes, such as feeding. Further, the exceedance of hydraulic thresholds leads to detachment of organisms from substrates and downstream transport, which, if exceeding natural drift rates, depletes the populations (Schülting et al., 2016; Auer et al., 2017). Thus, tolerant species (which own morphological or behavioral adaptations like claws or the ability to quickly crawl into the interstices) often dominate over sensitive ones (e.g., surface-dwelling taxa that are exposed to flow changes) in hydropeaked rivers, which feature altered biotic community structures as well as reduced biomass (Moog, 1993; Hayes et al., 2021). Further, the flow amplitude is directly linked to the area of the dewatered shoreline, which in turn affects stranding of organisms. Flooding and drying of shore areas additionally lead to challenging conditions for riparian vegetation, since processes like germination and plant establishment are constantly disturbed. The water level and related parameters such as drag forces are directly linked to the flow amplitude and were found to be a key parameter determining plant survival. Under hydropeaking, species that own adaptations like adventitious roots are therefore favored (Bejarano et al., 2018, 2020).

Ramping rate. Another feature of hydropeaking waves are the fast rates of change in the flow increase and decrease (Figs. 3 and 4B–C). There is evidence that the up-ramping rate is significantly linked to stream organism responses: fast flow increases reduce the time response for seeking shelter, thus leading to increased drift rates of aquatic organisms when hydraulic conditions exceed tolerance thresholds (Schülting et al., 2019; Smokorowski, 2021). The decrease of discharge during a hydropeaking event plays a minor role regarding downstream drift. However, down-ramping strongly affects the risk that aquatic organisms strand on previously inundated areas that fall dry as water recedes back into the main channel. This phenomenon is especially relevant for fish (e.g., Young et al., 2011; Auer et al., 2017) but has also been documented for macroinvertebrates. As a general rule, the faster the down-ramping rate, the higher the stranding risk as animals fail to conduct timely lateral shifts with the receding water table. Fish larvae, in particular, are at greater risk of becoming stranded. On the one hand, larvae are still weaker swimmers; on the other hand, fish larvae inhabit river areas especially prone to drying out or being cut off from the river after a hydropeak (Greimel et al., 2018b;

Table 2 Summary overview that links hydropeaking flow alterations to abiotic properties, ecological processes and impacts, and describes associated mitigation options.

Flow parameter	*Abiotic effects/change in state*	*Ecological process*	*Ecological impact*	*Response: mitigation recommendation*	*Key references*
Peak amplitude, flow ratio, magnitude	Change in hydraulic forces Change in water level and wetted width Increased (sub-) daily maximum flow magnitude Substrate mobilization/ scouring Decreased (sub-) daily minimum flow magnitude Fine sediment deposition, clogging of gravel bars	Habitat shifts (to refugial habitats) Hydraulic stress Downstream displacement of fish and macroinvertebrates (catastrophic drift) Scouring of algae from the substrate Inhibition of germination and growth performance Fish (egg) damage and macroinvertebrate removal Soil moisture deficit and water stress for plants Desiccation or freezing of fish eggs or macroinvertebrates Restricted fish movements Reduction of suitable aquatic habitats and oxygen supply, habitat loss within interstices	Increased mortality Reduced reproduction success Food depletion Reduced population biomass Reduction in community richness Selection of tolerant species	Reduce peak flow amplitude and flow ratio, especially during critical seasons/times Decrease maximum peak flow magnitude Increase minimum flow magnitude between hydropeaks	Bretschko and Moog (1990), Moog (1993), Casas-Mulet et al. (2015a,b), Irvine et al. (2015), Bondar-Kunze et al. (2016), Bejarano et al. (2018) and Hayes et al. (2021)
Ramping rate	Up-ramping: unnaturally rapid flow increase, quick increase in hydraulic forces Down-ramping: unnaturally rapid flow decrease, quick drying of previously wetted areas	Downstream displacement of fish and macroinvertebrates (catastrophic drift) Hampered plant germination Stranding Hampered plant germination	Increased mortality Reduced population biomass Selection of flow tolerant species	Lower ramping rates below ecologically relevant rates of change	Young et al. (2011), Bruno et al. (2016), Hayes et al. (2019), Moreira et al. (2019), Schülting et al. (2019) and Bejarano et al. (2020)
Duration	Extended periods of minimum and maximum flows	Increased likelihood of macroinvertebrate and fish (egg) desiccation and death following stranding Aquatic plant stress when emerged too long Riparian plant stress when inundated too long	Increased mortality Reduced population biomass Changes in species composition	Smoothen (sub-) daily hydrograph curves	Perry and Perry (1986), Casas-Mulet et al. (2015a,b) and Bejarano et al. (2018)
Peak frequency	Increased number of flow reversals entail recurring fluctuations of water level and hydraulic forces	Habitat shifts (to refugial habitats) Involuntary drift Stranding Frequent inundation of riparian areas	Higher energy consumption and less feeding time Reduced population biomass Reduced growth and reproduction success Increased mortality Changes in species composition (selection of tolerant species)	Lower hydropeaking frequency, especially of large peaks and during critical seasons (e.g., reproduction or early life-cycle stages)	Bauersfeld (1978), Schmutz et al. (2015) and Hayes et al. (2019)
Timing	Seasonality	Increased macroinvertebrate drift during warm period Increased fish stranding at larval stages and/or during cold period	Increase in above-mentioned impacts if hydropeaking occurs during sensitive times	Adapt mitigation frameworks such as flow rules to ecologically-sensitive times, e.g., by implementing an 'emergence window'	Kennedy et al. (2016), Greimel et al. (2018b), Hayes et al. (2019) and Moreira et al. (2019)
	Time of day	Increased macroinvertebrate and fish larval drift and fish stranding during night			
	Thermopeaking	Thermal modification can lead to increase or decrease in above mentioned drift- and stranding patterns depending on direction and organism	Changes in structural and functional community patterns Altered life cycle patterns Possible intensification or mitigation of some of the above-mentioned impacts	Reduce amplitude of temperature changes	Bruno et al. (2013), Casas-Mulet et al. (2015a,b, 2016), Schülting et al. (2016), Vanzo et al. (2016a) and Bondar-Kunze et al. (2021)

Hayes et al., 2019). In this context, the local morphological characteristics play an important role: The risk of stranding is potentially higher if low sloped and heterogenous riverbanks with coarse sediment are present. However, such river banks also provide better habitat conditions for young fish, compared with steep and homogenous riparian structures (Larrieu et al., 2021). Finally, studies showed that both rapid flow in- and decreases reduce germination success of flood-intolerant species of riparian vegetation (Bejarano et al., 2020).

Frequency and duration. Drift of macroinvertebrates was found to decrease quickly during the extent of the peak flow phase; in contrast, stranding often increases with the duration of peaking due to higher colonization rates of the shore habitats (Perry and Perry, 1986). The duration of dewatering in the ramping zone is also key to determine the potential survival of stranded organisms in isolated pools (Young et al., 2011) as well as in the subsurface or hyporheic zone (Casas-Mulet et al., 2015b). The frequency of general hydrological disturbances is known to affect aquatic communities. In the case of hydropeaking, some species, such as juvenile grayling (*Thymallus thymallus*) may show (temporal) adaptation behavior to recurring peaking (Auer, unpubl. data). However the effects may also accumulate with increased peaking frequency (Bauersfeld, 1978; Bruno et al., 2016). Increasing frequency and duration of hydropeaking was found to intensify stress on riparian vegetation and affect germination as well as plant survival (Bejarano et al., 2018, 2020).

Timing. The effects of hydropeaking on aquatic organisms can largely vary between seasons and even between different times of the day. One major reason for seasonal variation is that the sensitivity towards hydraulic stress is strongly life stage-specific. For example, as mentioned above, stranding can be observed mostly for fish larvae as fish become less susceptible to stranding as they grow in size (Hayes et al., 2019). In addition, the seasonal changes in water temperature strongly affect organism responses to hydropeaking as lower water temperature during winter lowers the activity of most species and subsequently affects drift and stranding patterns. Studies have shown that the drift and stranding differ between day and night because of a combination of light intensity and organism activity (Smokorowski, 2021). For example, macroinvertebrate drift is commonly lower during the night because insects actively seek flow-exposed areas during the night for feeding, among other reasons.

Ecological impacts linked to thermal alterations

Water temperature is a key physical property of river flows and a primary driver for community patterns of riverine organisms and for ecological processes. Hence, thermal modifications caused by the operation of hydropower can significantly affect river biota. However, the effects of thermopeaking on aquatic communities have not been extensively studied, and it remains a challenge to disentangle the effects of hydro- and thermopeaking (Bruno et al., 2013). In any case, thermal modification may act as an additional stressor on periphyton, macroinvertebrates and fish, leading to changes in structural and functional community patterns as well as to altered life cycle patterns. A study on periphyton development under combined hydro- and thermopeaking showed that sudden fluctuations in flow and water temperature affect biomass and community structure: cold thermopeaking in summer enhanced algal biomass and diatom development, whereas warm thermopeaking in winter led to decreased algal biomass development and an increase in green algae (Bondar-Kunze et al., 2021). Through a modelling approach, Casas-Mulet et al. (2016) illustrated how warm thermopeaking events encourage early salmonid embryo hatching in winter, and increase stranding mortality in alevin stages during dewatering events, with egg stages being less susceptible to desiccation. Further experimental studies have shown that hydropeaking-induced macroinvertebrate drift and fish stranding patterns may change in combination with warm and cold thermopeaking (Carolli et al., 2012). The directions of response are, however, quite variable and more research is needed to identify general patterns (Smokorowski, 2021) (Table 2).

Socio-cultural impacts: Ecosystem services

Hydropower production schemes and hydropeaking affect not only the biotic river community, but they can also influence other ecosystem services that river systems provide. In principle, hydropeaking can impact each ecosystem service that depends on the biotic and abiotic parameters previously described as flow, morphology, and sediment transport. In contrast to river biota, hydropeaking shows positive and negative relations with ecosystem services. For example, in late summer to early fall, only hydropeaking events provide suitable conditions for recreational services such as rafting and kayaking in Alpine rivers: during baseflow conditions, water depth and water velocity—two parameters directly linked to river flow—may not be sufficient to enable boating (Carolli et al., 2017b). Higher river flows due to hydropower production have also been linked with enhanced user preferences and with a higher aesthetical value (Pflüger et al., 2010). In contrast, hydropeaking also shows negative effects on ecosystem services: by affecting fish habitat and species communities. Hence, hydropeaking can negatively influence recreational services such as angling (Carolli et al., 2017a).

Mitigation measures

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 (Table 2). In this regard, hydropeaking mitigation measures can be grouped into two broad categories: (i) hydrological and (ii) morphological measures. While the first group of measures aim to modify the peak hydrograph directly, the second group seeks to mitigate adverse effects indirectly by improving hydraulic conditions in the affected river section (Greimel et al., 2018b; Table 3).

Table 3 Hydropeaking mitigation measures and emerging alternative storage systems—a non-exhaustive overview.

Measure group	*Measure type*	*Details*	*Related costs and concerns*
Hydrological mitigation: operational	Increase of residual flow magnitude	Higher environmental flow allocation to reduce drawdown range, esp. during critical periods	Decline in revenue Loss of flexibility
	Turbine flow limitation	Lower peak flow magnitude	Decline in revenue Loss of flexibility
	Anti-cyclical operation of different hydropower plants	Lower peak flow and increase baseflow for a more constant flow in the whole river system	Decline in earnings due to production during low demand Loss of flexibility Legal constraints (e.g., water table prescription in reservoir)
	Lower up- and down-ramping operations	Decrease flow ramping to avoid drift and stranding of organisms	Decline in revenue Loss of flexibility
Hydrological mitigation: constructional	Powerhouse outflow into a lake (or ocean or fjord)	Turbine outlet directly connected to a lake to avoid hydropeaking in the river	Lake too far away Construction costs Impact on lake ecosystem
	Powerhouse outflow into a side channel or tunnel	Parallel side channel or tunnel to evacuate the turbine water without impacting the river	Land availability Construction costs Groundwater impacts
	Compensation basin	Powerhouse outflow into a storage basin with a controlled outflow to the river	Land availability Construction costs Fluctuating water level (recreation) Volume depending on the turbine outflow
	Compensation cavern	Powerhouse outflow linked with an underground retention basin with a controlled outflow	High construction costs Volume depending on the turbine outflow
	Powerhouse outflow into a basin (of a run-of-river power plant)	Basin located on the river, controlling flow through turbines or weirs	Land availability Construction costs Fish migration, sediment transport
	Powerhouse outflow into lake and residual run-of-river flow release	Existing hydropower plant used in run-of-river mode for environmental flows release and new parallel system for peak flow production	Construction costs Decline in earnings due to run-of-river operations during low energy demand
Morphological mitigation: indirect measures	Channel widening	Widening of river cross-section to reduce peak amplitude and hydraulic forces	Land availability Construction costs
	Reconnection of tributaries and creation/ maintenance of side channels	Establish connectivity to instream flow refugia	Land availability Construction costs
	Channel restructuring: instream measures	Increase macro-roughness and enhance habitat structures	Legal and environmental constraints
Emerging alternative energy storage systems and complementary measures	Floating solar panels on reservoirs	Add additional energy generation source whilst lowering water evaporation losses	Construction costs Possible environmental constraints
	Inflatable balloons in reservoirs	Displacing water by balloons allows for a higher flexibility of energy production	Construction costs Operating costs Possible environmental constraints
	Compressing air into excavated caverns (air cushion underground caverns)	Underground caverns give additional water volume to the adjacent reservoir. In the caverns, air is used to displace water and subsequently to adjust water levels for hydropower production	Construction costs Operating costs
	Energy storage in batteries	Store energy in batteries and extract during phases of high demand	More research and development needed Construction costs
	Pumped-storage facilities	Turning storage hydropower into pumped-storage facilities guarantees production flexibility while not releasing all of the water into the river	Land availability Construction costs
Measure integration	Combination of measures	Combinations of different mitigation measures may lead to more cost-effective outcomes, for example, by combining a compensation basin and channel widening measures as depicted in Fig. 6.	

Modified from Person É (2013) *Impact of Hydropeaking on Fish and Their Habitat.*; Greimel F, Schülting L, Wolfram G, Bondar-Kunze E, Auer S, Zeiringer B et al. (2018b) Hydropeaking impacts and mitigation. In: Schmutz S and Sendzimir J (eds.), Riverine Ecosystem Management, pp. 91–110, Springer.

Hydrological mitigation measures

Hydrological improvements can be attained by either (a) operational or (b) constructional measures. The first adjusts the hydropower plant's mode of operation to reduce peak-intensity parameters such as lowering ramping rates, flow amplitude, or hydropeaking frequency. These hydrological changes may bring direct environmental improvements; for example, by reducing down-ramping to below critical thresholds fish stranding can be avoided (Fig. 5). Also, higher baseflows can be released to avoid critical river reaches falling dry between peaks (Hayes et al., 2019; Moreira et al., 2019). However, from the economic perspective, mitigation approaches that restrict turbine operation lead to lost profits due to loss of flexibility (Greimel et al., 2018a; Table 3).

The second sub-group, structural measures, includes add-on constructions to the existing hydropower facilities. If the river valley offers enough space, the construction of re-regulation or retention basins is an effective option to dampen hydropeaking intensity and increase minimum flows. The hydrological effects in the tailrace can be similar to those of operational measures mentioned earlier (Figs. 5 and 6). Depending on its size, retention basins usually do not require changes in the hydropower plant's operational mode as they catch and retain the peak flow in the basin, and ensure a smoother water release to the river. Except for reservoir construction investments, retention basins do not incur permanent losses of profits (Greimel et al., 2018a; Anindito et al., 2019). Another option to change hydropeaking hydrology is to build a hydropeak diversion power plant that pipes peak flows to a downstream facility. From an operator's perspective, this measure can increase economic revenue after investments are redeemed. From an ecological perspective, results may be far from optimum since the affected river reach turns into a residual flow stretch that requires specific environmental flow allocations. Hydro-numeric simulations for the Austrian GKI case study (see Table 4) show that peak-diversion can indeed lower fish stranding risk (Moreira et al., 2020). However, the hydropeaking stretch is only moved further downstream—albeit larger rivers can potentially cope better with (comparably smaller) peaks than smaller rivers. A further solution to avoid hydropeaking in rivers is to divert the peak into a lake or construct a retention basin at the turbine outflow of the diversion hydropower plant (Table 3).

Morphological measures: Indirect mitigation

The second mitigation block includes physical modifications in the channel of the hydropeaked river to improve habitat structures and/or to create refugial areas. Such morphological measures seek to mitigate adverse effects by indirectly improving hydraulic conditions in the river, but not affecting hydropower operation (Fig. 6). Channel widening or side channel maintenance can reduce flow amplitude and associated hydraulic forces, and tributary reconnection can aid recruitment of aquatic biota by providing spawning and rearing areas without hydropeaking. Placement of large blocks and deflectors may also enhance structural heterogeneity of the channel, helping to dissipate flow energy and offering refugia to fauna. A recent fish population study, however,

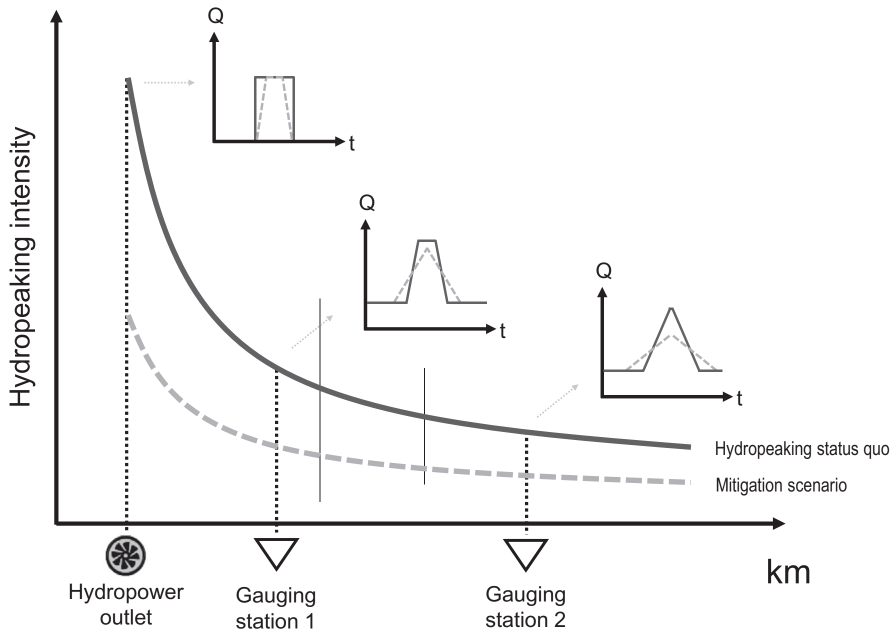

Fig. 5 Hydrological changes through operational and/or constructional measures can lower hydropeaking intensity in the affected river reach. Shown here is how hydropeaking intensity, such as down-ramping rate, changes in downstream direction (bottom graph) and how these hydropeaking waves are measured at the hydropower outlet and at two successive gauging stations (top three graphs). The dark grey solid line illustrates a hydropeaking status quo, the light grey dashed line a mitigation scenario based on hydrological improvements. Modified from Muhar S, Arnaud F, Aschwanden H, Binder W, Broggi M, Greimel F et al. (2019) Restoration. New life for the rivers of the Alps. In: Muhar S, Muhar A, Egger G, and Siegrist D (eds.), *Rivers of the Alps. Diversity in Nature and Culture*, pp. 320–343, Berne: Haupt.

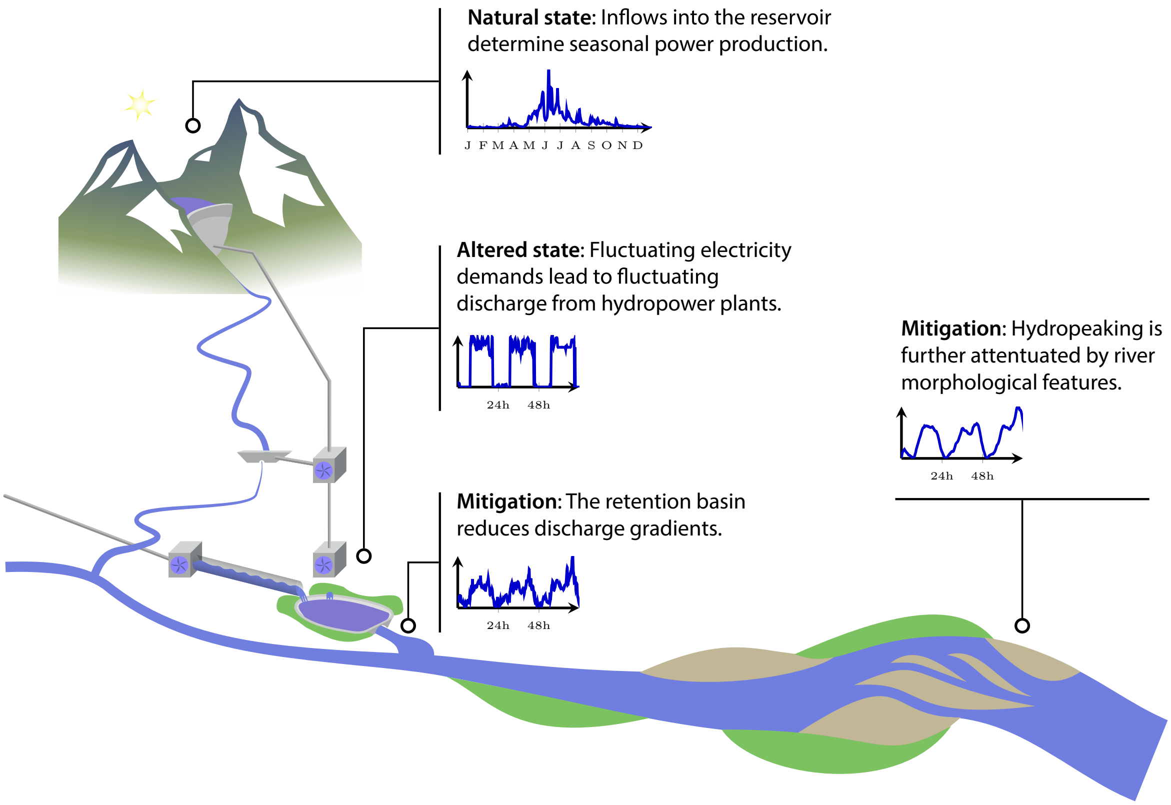

Fig. 6 A systems perspective on hydropeaking mitigation: how retention basins and morphological measures (e.g., channel widening, side channel creation) reduce peak intensity. Modified from Philipp Falke (MeteoSwiss).

indicated that 'the full benefits of river rehabilitation measures can only become visible if hydropeaking intensity is reduced at the same time' (Hayes et al., 2021). In this regard, it is not surprising that the combination of hydrological and morphological measures is projected to lead to greater ecological improvements at national scale (Greimel et al., 2018a).

Emerging alternative energy storage systems and complementary measures

Aside from the measures described above, which have hardly changed since the mid-1980s (Smokorowski, 2021), new (energy system-specific) methods or storage systems are arising. These solutions include, for example, the use of floating solar panels on reservoirs (Farfan and Breyer, 2018), inflatable balloons in reservoirs, or compressing air into excavated caverns to displace water (Storli and Lundström, 2019; Table 3). Also, electricity storage in electric vehicles to compensate for peak energy demands has been suggested (Román et al., 2019). A recent study suggests that by 2025 batteries will become economically viable to aid hydropeaking mitigation (Anindito et al., 2019). Indeed, affordable energy storage and solar systems are deemed sufficient to avoid severe hydropeaking in the renewable energy systems of the future (Haas et al., 2019).

Overall, such 'traditional' and new innovative measures or storage systems are needed to guarantee a *quasi*-green energy system and sustainable peaking production in the future, despite inevitable impacts (as discussed above). To date, however, hydropeaking is, at its heart, still a controversial issue. It is commonly recognized that hydropeaking cannot (yet) be entirely avoided. In this regard, its socio-economic benefits and balancing role must be weighed against its environmental effects.

Mitigation case studies

Despite the phenomenon of hydropeaking being globally widespread, there is still a lack of mitigation measures to be comprehensively implemented. Indeed, the literature contains only few such case studies. Most of them are from North America and Europe (Moreira et al., 2019). Some of these case studies are highlighted in Table 4 and include mitigation through a compensation basin, diversion hydropower plant, or operational restrictions.

For instance, the Upper Inn River, Austria, is affected by frequent hydropeaks with ramping rates exceeding ecological thresholds, heavily impacting fish populations. As a mitigation measure, a diversion power plant is currently being constructed. Once in

Table 4 Case studies illustrating hydropeaking and mitigation measures worldwide.

Name of site	*River, country*	*Coordinates*	*Current state and mitigation approach*	*Evaluation of mitigation measures*	*Key reference(s)*
Gemeinschaftskraftwerk Inn (GKI)	Inn River, Austria and Switzerland	47°4′4.78″N, 10°39′54.37″E	Newly constructed hydropower station diverting water from the Upper Inn River at the Swiss border 23 km downstream to the Austrian powerstation Prutz. Environmental flows and operational hydropeaking restrictions are implemented in the diversion stretch.	Construction still in progress.	Moreira et al. (2020) https://www.gemeinschaftskraftwerk-inn.com
Hydropower plant Alberschwende	Bregenzerach River, Austria	47°28′25″N, 9°50′ 59″E	In 1992, a new diversion hydropower plant was built together with a retention basin (volume: 150,000 m^3) to buffer hydropeaking. Additionally, base flow is increased slowly 24 h prior to peaking operation to reduce total peak amplitude.	Reduction of peak flow ratio and ramping rate lead to macroinvertebrate biomass recovery, but regarding fish no improvement was documented.	Grasser et al. (1998) and Parasiewicz et al. (1998)
Hydropower plant Innertkirchen	Hasliaare River, Switzerland	46°42′30″N, 8°13′29″E	The following measures were realized from 2013–2016: construction of retention basins (total volume: 80,000 m^3), morphological instream structures, increase of base flows.	A decrease of ramping rates led to an increase of macroinvertebrate biomass and fish productivity; however, fish stranding could not be significantly reduced.	Tonolla et al. (2017) and Schweizer et al. (2021)
Sokna kraftverk	Lundesokna River, Norway	63°08′59.5″N, 10°18′23.1″E	Constructed in 1964, the Sokna hydropower plant affects the Lundesokna River 5 km before it reaches the unregulated Gaula River. The upcoming relicensing process will consider either operational or constructional measures, given the legal requirements and the high conservation interest of the Gaula River.	Not yet implemented.	Casas-Mulet et al. (2016)
Steephill Falls hydropower plant	Magpie River, Canada	48°4′41.17″N, 84°44′18.23″W	From 2002–2007, an adaptive management experiment was run to test the notion that minimum flow allocations and ramping rate restrictions provide ecological benefits.	Macroinvertebrate abundance and diversity decreased after ramping restrictions were lifted, implying that restricted operations were protective of river biota.	Smokorowski (2010)
Gordon Power Station	River Gordon, Tasmania, Australia	42°44′25.79″S, 145°58′56.73″E	Adaptive management principles were applied to establish an optimal ramp-down rule to minimize seepage while allowing operational flexibility. Down-ramping is deemed necessary when bank saturation exceeds defined trigger values and power station discharge is above 150 $m^3 s^{-1}$.	The revised ramp-down rule was monitored and assessed since 2012 and was found to reduce seepage erosion.	https://www.hydro.com.au/environment/environmental-management/monitoring-the-gordon-river

operation, this facility will reduce ramping rates to levels considered adequate for protection of young-of-the-year fish, whilst enabling increased energy production in the region (Moreira et al., 2020). A diversion power plant and a compensation basin was constructed at the Austrian Bregenzerach River in the early 1990s, and evaluations of this measure showed a positive trend for macroinvertebrates but not for fish (Parasiewicz et al., 1998). The Swiss Hasliaare River is one of the best-known examples of compensation reservoirs. Recent evaluation revealed that particularly the combination of basins and instream measures led to achieving sought ecological targets (Schweizer et al., 2021; Table 4). The heavily hydropeaked Lundesokna River, Norway, is a major tributary of the Gaula River, one of the last unregulated rivers in Norway of high conservation value that entails special requirements for environmental protection. To date, no mitigation measures have been set in place. However, the upcoming relicensing process of the Sokna hydropower station pushes the conversation between the local council and the energy company to implement either operational constraints or structural measures to target key environmental needs in both rivers (Table 4). The Gordon Power Station is the largest power station in Tasmania, Australia. Hydropeaking at the Gordon was projected to increase following the commissioning of an undersea power cable to connect Tasmania with mainland Australia. A research and monitoring program was implemented from 2002 to 2020 to detect impacts on the ecology and fluvial geomorphology of the Gordon River caused by hydrologic changes resulting from joining the national electricity market. Under the program, a ramp-down rule to minimize seepage erosion due to hydropeaking was devised, implemented and refined through adaptive management (Table 4).

Synthesis

In this chapter, we illustrated links between peaking-power production and ecosystem integrity/function, as well as gave an overview of mitigation measures from a river-specific and energy-grid-specific perspective. In summary, hydropeaking remains a controversial topic. Storage hydropower offers to date the best way to store energy at the large scale, and the flexible energy generation capacity of start-stop production makes peaking power an indispensable part of the power fleet, in particular that of renewable energy systems with increased grid volatility due to solar and wind power generation. However, considering the manifold ecological impacts, it is necessary to establish and implement timely mitigation measures, despite their potential effects on energy market hydropeaking drivers. When considering mitigation strategies, both socio-economic and environmental values should be considered in trade-off analysis. However, it is necessary to acknowledge the existence of strong legislative frameworks than can be contradictive, for example, pertaining to the expansion of renewable energies and ecosystem conservation, making the decision-making process difficult. Future research should focus on evaluating and adjusting implemented mitigation measures based on complex realities, as well as acknowledge the diversity of bio-physical processes in rivers affected by hydropeaking worldwide.

Knowledge gaps

The following list presents a set of open core questions that, if answered, would aid the sustainable management of hydropeaked rivers.

1. 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; armoured vs. loose (mobile) bed rivers), groundwater influence (e.g., hyporheic vs. surface-dominant flows), or biocoenotic regions such as fish regions (headwaters vs. lowland rivers)?
2. How do prior river conditions influence ecosystem impacts of hydropeaking?
3. What are the direct consequences of organism drift and stranding on the individual organism and population level?
4. What are the effects of hydropeaking on the food-web structure in different river types and regarding the longitudinal gradient of a river?
5. Which biological metrics are most sensitive and could be included into a stressor-specific biological assessment method?
6. What are functional processes that govern hydropeaking impacts? Are results of impact analyses consistent through different spatio-temporal levels (e.g., from an event at the gravel bar to multi-year effects on wider regional hydroclimatic scales) so that generalized processes can be deducted?
7. How does the ecosystem stressor of hydropeaking interact with other pressures such as channelization, river-floodplain disconnection and tributary fragmentation, land-use change, water quality alteration, or (piscivorous) predators?
8. How can ecosystem impacts be assessed from the context of climate change and future socio-economic priorities?
9. What economic and social constraints hinder the spatial and temporal implementation of mitigation measures?
10. What kind of measures best mitigate the (ecological) consequences of hydropeaking, and how can their effectiveness be best quantified to serve as a decision-support for sustainable hydropeaking management?

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