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Restless rivers: impacts of frequent hydropeaking on habitat dynamics

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ABSTRACT

Storage hydropower is central to the energy transition, yet its flexible mode of operation can generate frequent flow fluctuations, known as hydropeaking. This paper synthesises recent empirical and methodological advances to show that the ecological impacts of hydropeaking depend not only on the magnitude of individual flow fluctuations, but also on the frequency of these fluctuations. In Alpine hydropeaking rivers, flow fluctuations occur on average three times per day, with only minor seasonal differences. This frequency is 20–60 times higher than under natural flow conditions on an annual basis and 49–78 times higher during spring, an ecologically sensitive period. This high frequency of flow fluctuations drives cumulative ecological impacts, including repeated fish stranding and invertebrate drift. The underlying mechanisms operate at the patch scale, where recurrent shifts in habitat conditions lead to a pronounced increase in habitat dynamics. In practical terms, habitat persistence and temporal availability decline, as does the spatio-temporal connectivity of habitats. Three recently developed metrics (M1, M2, M3) quantify patch-scale habitat dynamics and provide a practical tool for assessing cumulative ecological impacts in a spatially explicit manner.

Key words: ecological impact, energy transition, flow alteration, hydropower, patch-scale, river management

HIGHLIGHTS

- Hydropeaking in Alpine rivers generates three flow fluctuations per day, a frequency 20–60 times higher than under natural conditions.
- Frequent flow fluctuations cause cumulative impacts via repeated fish stranding and invertebrate drift.
- High hydropeaking frequency intensifies habitat dynamics at the patch scale.
- Three recently developed metrics quantify habitat persistence (M1), temporal availability (M2) and connectivity (M3).
- Patch-scale processes enable spatially explicit mitigation of hydropeaking impacts.

GRAPHICAL ABSTRACT

1. INTRODUCTION

The Alpine region hosts numerous storage hydropower plants that supply about one-quarter of Switzerland's and about one-third of Austria's electricity production (BMK 2024; SFOE 2025). In the context of the energy transition, these plants are becoming increasingly important as they compensate for the more volatile electricity generation from other renewable sources, such as wind and solar power. Storage hydropower thus makes a crucial contribution to electricity security and supply (Quaranta *et al.* 2022; Koolen *et al.* 2023).

However, the flexible, on-demand operation of storage hydropower results in frequent and often abrupt flow fluctuations (i.e. hydropeaking) in Alpine rivers. These artificially induced flow fluctuations increasingly conflict with biodiversity conservation objectives (Venus *et al.* 2025). Numerous studies demonstrate that hydropeaking can have substantial ecological impacts (e.g. reviews by Hayes *et al.* 2022; Bipa *et al.* 2024; Bozeman *et al.* 2024).

These impacts primarily arise from increased spatio-temporal habitat dynamics. During flow increases, high current velocities can induce the downstream drift or displacement of organisms. During flow reductions, shallow habitats dewater, increasing the risk of organism stranding. Thus, frequent flow fluctuations can generate cumulative ecological effects that progressively impair population dynamics, reduce species diversity, and ultimately compromise the ecological status of rivers (Schmutz *et al.* 2015; Hayes *et al.* 2025).

Field data from Austria indicate that river reaches with a mean frequency of more than one flow fluctuation per day exhibit a significantly poorer ecological status (Figure 1). While this assessment did not explicitly consider the magnitude of individual flow fluctuations, the findings suggest that hydropeaking frequency, and the repeated stranding and/or drifting of organisms it causes, may constitute a key factor limiting the ecological condition of Alpine rivers (Hayes *et al.* 2025; Auhser *et al.* in review; Merl *et al.* 2026).

As renewable energies continue to expand, the role of storage hydropower as a flexible, low-carbon energy-balancing source is expected to grow further (Quaranta *et al.* 2022). Projections indicate that the anticipated growth in wind and solar generation will require a ninefold increase in flexible balancing capacity by 2050 (Koolen *et al.* 2023). Therefore, it is foreseeable that hydropeaking frequency, resulting from the flexible operation of storage hydropower, will continue to rise, further intensifying pressure on Alpine rivers.

This article aims to draw attention to the frequency of hydropeaking and to highlight its significance in trading off between energy production and river restoration, particularly with respect to biodiversity protection. Building on and complementing recent empirical and methodological advances, the paper develops a process-based synthesis of how hydropeaking frequency translates into cumulative ecological impacts through alterations of patch-scale habitat dynamics. First, we quantify hydropeaking frequency in Alpine rivers in Switzerland and Austria. Second, we employ reduced-complexity modelling to illustrate the cumulative ecological impacts of frequent hydropeaking, using fish stranding and invertebrate drift as examples. Third, we show how three recently developed metrics (M1, M2, M3; Bätz *et al.* 2025) can operationalise

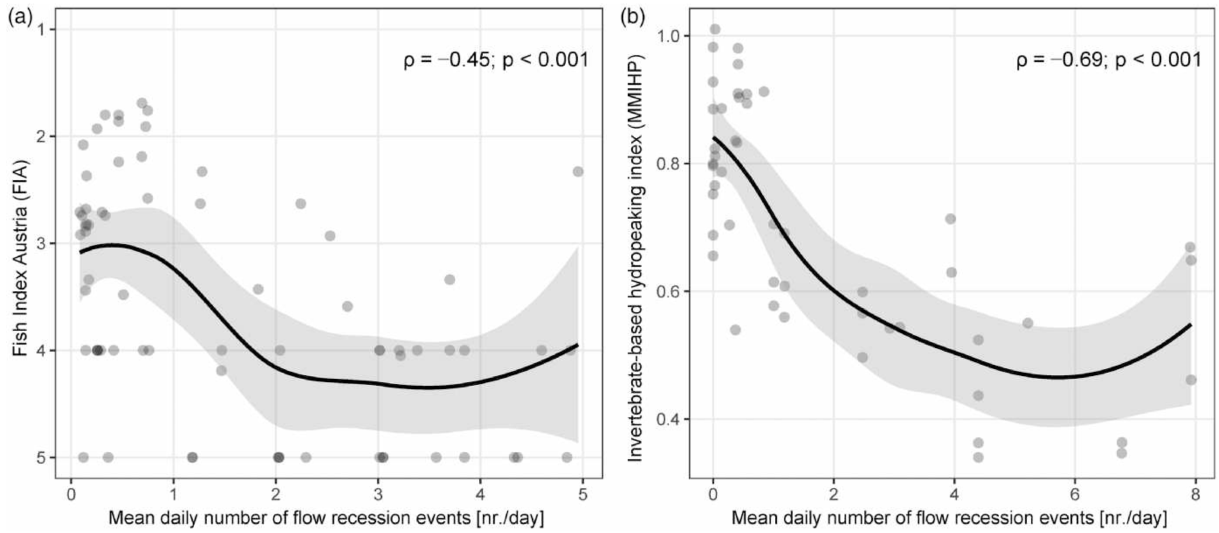


Figure 1 | Relationship between the mean number of daily flow recession events (including both natural and hydropeaking-induced events) and (a) the Fish Index Austria (FIA; indicator of the status of the fish population structure and community; scale: 1 = high, 5 = low) in Austrian grayling rivers (data from Hayes *et al.* 2021), and (b) the MMIHP, a multi-metric invertebrate-based hydropeaking index (scale: 1 = high, 0 = low; data and index from Auhser *et al.* in review). The mean number of flow recession events was calculated according to the method described in Section 2 over the five years preceding fish sampling and the six months preceding macroinvertebrate sampling. Both curves show the smoothed relationship between flow recession frequency and ecological status (LOESS smoothing), and the shaded band represents the 95% confidence interval of the fitted trend. The Spearman rank correlation coefficient (ρ) and the associated p-value are shown above. Adapted and translated from Bätz *et al.* (2026).

patch-scale habitat dynamics in terms of temporal availability, habitat persistence, and spatial shifts of habitats. Finally, we discuss how these findings may inform ecologically effective mitigation strategies.

2. HYDROPEAKING FREQUENCY IN THE ALPS

Building on Hayes *et al.* (2025), we quantified the frequency of ecologically relevant flow fluctuations in natural and hydropeaking Alpine rivers in Switzerland and Austria. Following Greimel (2022), we conducted the analysis using the R package *hydropeak* (Grün *et al.* 2021). We identified ecologically relevant flow fluctuations by comparison with reference thresholds derived from natural rivers.

These thresholds are based on a regression analysis of 419 Austrian reference rivers and describe the typical maximum natural rate of discharge change, accounting for river size through mean discharge (MQ). This approach allows for an objective comparison of rivers of different sizes, eliminating the need for subjective or site-specific definitions. At a 15-minute resolution, the typical maximum natural rates of discharge change are approximately 3–5 m^3/s for small rivers (MQ 5–10 m^3/s), 9–12 m^3/s for medium rivers (MQ 30–50 m^3/s), and 15–18 m^3/s for large rivers (MQ 80–100 m^3/s).

For the analysis, rates of discharge change exceeding 20% of the natural reference threshold were classified as ecologically relevant. Sensitivity analyses indicate that rates below this threshold generally represent minor hydrological variability with limited ecological relevance. In contrast, higher rates of discharge change are increasingly associated with measurable ecological impacts, including the dewatering of shallow habitats (i.e. stranding) during flow recession and the elevated current velocities that lead to organism drift during flow increases (Zeiringer *et al.* in prep.).

Results show that, on an annual basis, hydropeaking generates a mean of approximately 20 times more ecologically relevant flow fluctuations than glacier-fed rivers and up to 60 times more than rainfall-dominated rivers (Figure 2). Glacier-fed rivers typically exhibit one flow fluctuation every two days, primarily in the summer due to the diurnal rhythm of glacier melt. Rainfall-dominated rivers respond mainly to precipitation events (e.g. thunderstorms) and display highest dynamics during summer, with an average of one flow fluctuation every eleven days. In contrast, under hydropeaking, flow fluctuations are primarily driven by electricity demand and plant operation. The results (Figure 2) indicate a mean daily frequency of three ecologically relevant flow fluctuations per day and substantial variability (25th – 75th percentile: 1–4

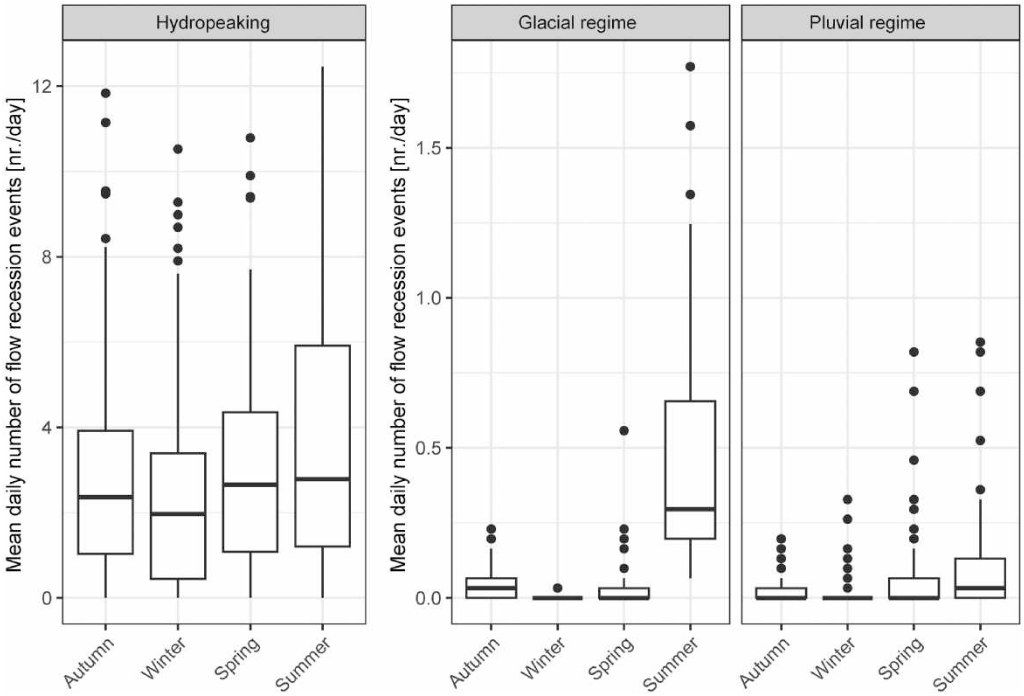


Figure 2 | Mean number of daily flow recession events in Alpine rivers in Switzerland (*n* = 43) and Austria (*n* = 44), grouped by hydro-ecological seasons (autumn: September–November; winter: December–February; spring: March–May; summer: June–August). Hydropeaking rivers (*n* = 36), glacier-fed rivers (*n* = 15), and rainfall-dominated rivers (*n* = 36). Data from 2015 to 2020. Y-axes differ in scale (data from Hayes *et al.* 2025). Adapted and translated from Bätz *et al.* (2026).

nr./day), with only minor seasonal differences. Similar hydropeaking frequencies have been reported for rivers in Italy (Zolezzi *et al.* 2009), Great Britain (Archer & Newson 2002), New Zealand (Clausen & Biggs 1997) and the USA (Li & Pasternack 2021).

Differences are particularly pronounced during ecologically sensitive periods. In spring (March–May; Figure 2), which coincides with the emergence and early larval stages of brown trout and the key development and emergence phases of many aquatic invertebrates, hydropeaking results in a mean of three ecologically relevant flow fluctuations per day. During the same period, rainfall-dominated rivers experience only a mean of one flow fluctuation every 16 days, and glacier-fed rivers experience one every 26 days. Thus, hydropeaking frequency is 49–78 times higher than under natural flow conditions.

Even during the summer (June–August), a sensitive period for the development of juvenile fish, hydropeaking frequency remains markedly elevated, averaging 3.7 flow fluctuations per day. This corresponds to roughly seven times the frequency observed in glacier-fed rivers and 39 times the frequency observed in rainfall-dominated rivers.

3. CUMULATIVE ECOLOGICAL IMPACTS OF HYDROPEAKING

The high frequency of hydropeaking suggests that ecological impacts arise not only from individual flow fluctuations, but also from their cumulative effects. This is particularly relevant during ecologically sensitive seasons and for less mobile life stages, such as fish larvae, juvenile fish, and aquatic invertebrates. However, cumulative impacts resulting from repeated flow fluctuations are difficult to detect directly in the field.

To explore these processes, we use process-oriented, reduced-complexity modelling approaches. Rather than providing quantitative predictions, these models use exploratory scenarios based on experimental data to clarify the mechanisms underlying repeated flow fluctuations. As illustrative examples, we examine two key mechanisms directly linked to hydropeaking frequency (Section 2): fish stranding resulting from repeated flow recession events and invertebrate drift resulting from frequent flow increase events.

3.1. Modelling fish stranding

Immediately after hatching, the swimming performance of larvae and juvenile fish is not yet fully developed. Consequently, they preferentially occupy shallow shoreline habitats with low current velocities (Hayes *et al.* 2024). However, these habitats are particularly prone to rapid and frequent dewatering during recurring flow recession events (Vanzo *et al.* 2016; Bätz *et al.* 2025).

The modelling approach is based on six flume experiments investigating the stranding of juvenile nase (*Chondrostoma nasus*; Auer *et al.* 2023). For simplicity, the model assumes a closed population in which all individuals are located within an affected area. Furthermore, the model assumes that stranded fish die, and that natural mortality is negligible. In the experiments, the fish were exposed to either single or repeated flow recession events. In the latter case, individuals could potentially develop a behavioural learning response. Based on these data, juvenile nase density trajectories were simulated under two scenarios: with and without a learning effect.

The results show that, although the density declines more slowly in the learning scenario, both trajectories converge after approximately 50–75 flow recession events (Figure 3(a)). These results suggest that behavioural adaptation alone is unlikely to compensate for the cumulative impacts of repeated stranding events. This finding is consistent with Schmutz *et al.* (2026), who showed that behavioural adaptation provides only limited protection against repeated stranding under frequent hydropeaking conditions.

3.2. Modelling invertebrate drift

In natural rivers, invertebrate drift is predominantly an active process that serves functions such as foraging, reproduction, or predator avoidance (Naman *et al.* 2016). Involuntary, passive drift typically occurs only during rare flood events. However, hydropeaking induces abrupt increases in current velocity, leading to frequent and largely involuntary drift events (Gibbins *et al.* 2007; Bruno *et al.* 2016; Schülting *et al.* 2023). The intensity of this drift depends strongly on local habitat conditions and the related invertebrate community composition (Aksamit *et al.* 2021; Tonolla *et al.* 2023; Friese *et al.* 2025).

To estimate cumulative impacts, we developed a modelling approach based on drift data from 90 controlled flume experiments (Schülting *et al.* 2023). The proportion of individuals lost during drift served as the basis for four scenarios combining various current velocities and rates of stage increase. Additionally, the model included incoming drift from upstream communities equivalent to 5% of the initial invertebrate density. The experiments were conducted under baseline

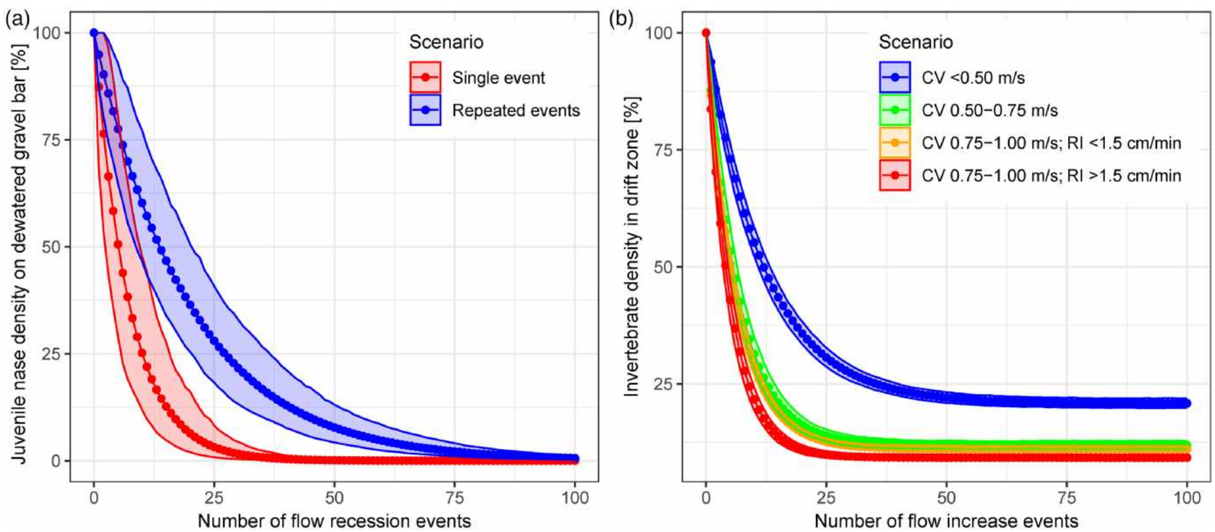


Figure 3 | (a) Modelled decline of juvenile nase density (Chondrostoma nasus, 23–30 mm) under repeated flow recession events (rate of stage recession: 1.5 cm/min). Shown is the mean relative density per flow recession event for the two scenarios with and without a learning effect (data from Auer *et al.* 2023; figure adapted from Hayes *et al.* 2025). (b) Modelled decline of invertebrate density in response to repeated flow increase events, based on experimentally determined mean drift rates (data from Schülting *et al.* 2023; CV = current velocity; RI = rate of stage increase). The curves show the mean relative density per event; the shaded area represents the 95% confidence interval from 1,000 simulations. Adapted and translated from Bätz *et al.* (2026).

low-current-velocity habitat conditions (<0.5 m/s) prior to exposure, which limits the transferability of the results to other hydraulic settings.

All scenarios show a rapid invertebrate density decline (Figure 3(b)). When exposed to high current velocities (>0.5 m/s), values stabilise at only 10–14% of their initial density after 25–30 flow increase events. The rate of stage increase has a detectable, albeit smaller, effect. Even when exposed to lower current velocities (<0.5 m/s), density remains well below the initial level in the long term (approximately 21–22% after 50–75 events). This pattern is consistent with repeated hydropeaking flume experiments by Bruno *et al.* (2016), which showed a strong initial drift response followed by reduced drift during subsequent events, likely reflecting depletion of susceptible individuals and partial recolonisation between events.

3.3. Consistent effects

Although fish stranding (repeated exposure to dewatering) and invertebrate drift (increased current velocity) arise from different immediate processes, both examples reveal consistent cumulative patterns. Losses associated with frequent hydropeaking occur rapidly and cannot be sufficiently compensated by behavioural adaptation in fish or by incoming drift from upstream populations of invertebrates.

The interpretation of the models is constrained by their simplified assumptions and experimental data basis. Nevertheless, the models provide a robust qualitative assessment of the potential cumulative ecological impacts resulting from repeated hydropeaking events. Combined with field data from Austrian rivers (Figure 1), which demonstrate a deterioration in ecological status with an increase in the frequency of flow fluctuations, the models support a coherent process-based understanding of the underlying mechanisms.

These findings suggest that the frequency of hydropeaking acts as a key factor in controlling ecological impacts: recurring flow fluctuations generate pronounced cumulative effects over time. This establishes a direct link between hydrological dynamics, ecological processes, and cumulative ecological impacts.

4. INFLUENCE OF HYDROPEAKING FREQUENCY ON HABITAT DYNAMICS

4.1. Natural habitat dynamics at patch scale

The interaction between flow regime and channel morphology generates a dynamic mosaic in which habitat conditions (i.e. hydraulics, temperature, and turbidity) vary over time at the patch scale (Stanford *et al.* 2005; Antonetti *et al.* 2023). A patch is defined as a geographically fixed area that aligns with the spatial and temporal perception of a given species and its respective life-cycle stage (Bätz *et al.* 2023). In contrast, 'habitat' refers to the set of environmental conditions that support the life cycle of a given species and may shift within or occur across multiple patches.

While channel morphology determines the spatial diversity of habitat conditions at the patch scale, the flow regime governs their temporal persistence and dynamics (Tockner *et al.* 2000; Bätz *et al.* 2023). For example, summer flow fluctuations in glacier-fed rivers (Figure 2) produce daily pulses of habitat conditions across the entire mosaic, resulting in recurrent shifts between different habitat conditions within patches. In contrast, rainfall-dominated rivers are characterised by longer periods of stable or gradually changing flow conditions, interrupted primarily by episodic flood events, resulting in substantially less frequent pulses of habitat conditions.

The spatial manifestation of this dynamic depends on morphological complexity. Shallow, morphologically simple river reaches respond more strongly to flow fluctuations than deeper or more structurally complex reaches. As a result, some patches experience more frequent and more pronounced habitat shifts than others (Weber *et al.* 2013; Bätz *et al.* 2025).

Aquatic organisms have adapted their life cycles and survival strategies to the naturally occurring dynamics of their local habitats over evolutionary timescales (Poff & Ward 1990). Particularly relevant characteristics of the flow regime include the magnitude, rate of change, duration, frequency of flow fluctuations, as well as their seasonal timing (Poff *et al.* 1997). For example, trout spawn in late autumn, and their eggs develop during the winter low-flow period (Figure 2), thereby reducing the risk of redds being scoured, dewatered, frozen, or clogged (Unfer *et al.* 2011). Some invertebrates, such as mayflies of the genus *Baetis*, attach their eggs to stones just below the waterline in shallow shoreline patches. This strategy relies on dry phases in these patches remaining spatially limited and occurring only rarely (Kennedy *et al.* 2016). Laboratory experiments show that hatching success declines sharply after five hours of dewatering and approaches zero after approximately nine hours, with temperature and humidity further amplifying these effects (Jaulin Gautronneau *et al.* 2026).

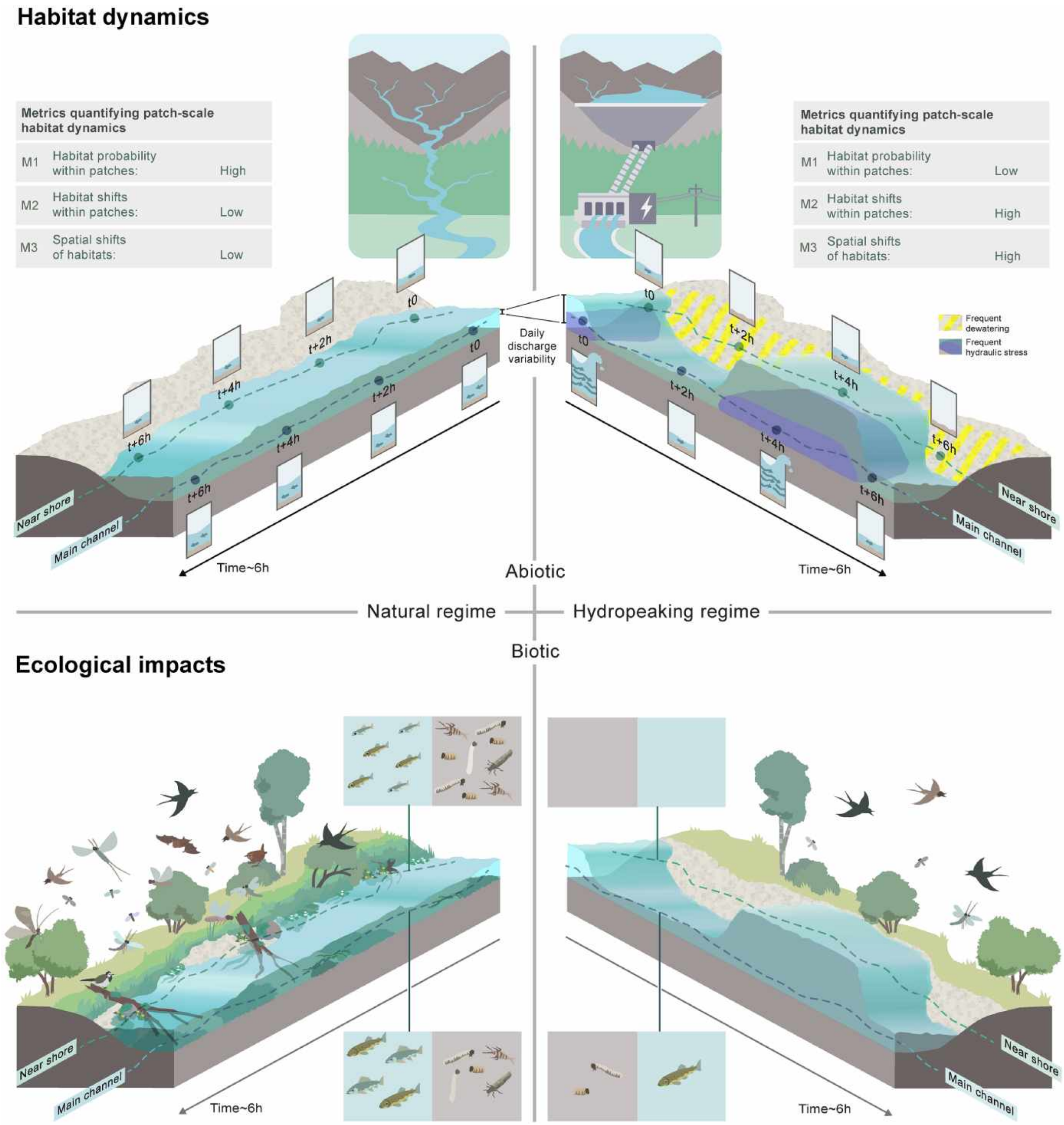


Figure 4 | Infographic of how frequent flow fluctuations caused by hydropeaking influence patch-scale habitat dynamics and organisms living within and along the river. Adapted and translated from Bätz *et al.* (2026). **Habitat dynamics (upper panel)**: Illustrates changes in discharge over approximately six hours within a river reach under natural flow conditions (left) and under hydropeaking conditions (right). For two representative patches (a shoreline patch and a patch in the main channel), habitat conditions are shown at four time steps (t_0 to t + 6 h). The three metrics (M1, M2, M3; see Box 1) summarize the extent to which patch-scale habitat dynamics differ between hydropeaking and natural flow conditions. **Ecological impacts (lower panel)**: Impacts on aquatic organisms, such as invertebrates (e.g. insect larvae) and fish, are illustrated for the same two patches. The infographic also shows how alterations in habitat dynamics propagate to riparian vegetation and the food web. For example, reduced emergence of aquatic insects may decrease food availability for terrestrial predators such as birds. **Interpretation**: Under natural flow conditions (left panel), shallow shoreline patches provide persistent and diverse habitat conditions for juvenile fish and invertebrates. Under hydropeaking conditions (right panel), however, these patches are regularly dewatered, which increases the risk of stranding or desiccation of eggs and larvae. Habitat dynamics also intensify for patches in the main channel, leading to more frequent invertebrate drift and increased relocation of fish to alternative patches. Over time, these increased habitat dynamics may reduce population size and species diversity, ultimately altering the ecological status of entire river reaches.

4.2. Alteration of habitat dynamics by hydropeaking

Hydropeaking fundamentally alters natural habitat dynamics by inducing rapid and frequent changes in water stage and current velocity at the patch scale. Such rapid fluctuations are difficult for organisms to anticipate. The processes of fish stranding and invertebrate drift, as described in Section 3, exemplify ecological mechanisms that manifest within individual patches (Figure 3).

Whether and to what extent a patch is affected by dewatering or increased current velocity depends on the magnitude and frequency of individual flow fluctuations. Consequently, not all patches experience dewatering equally often, nor are all patches equally exposed to elevated current velocities. Therefore, the ecological consequences of hydropeaking frequency emerge in a spatially heterogeneous and asynchronous manner within a river reach, concentrating in specific patches.

The mechanism behind fish stranding (repeated dewatering) and invertebrate drift (repeated increased current velocities) are just two examples of broader alterations to habitat dynamics. Hydropeaking reduces the temporal availability and persistence of habitats, as well as their spatio-temporal connectivity (Bätz *et al.* 2025; Chen *et al.* 2026). These attributes directly influence the life-cycle success, survival probability, and reproductive success of many species (Winemiller *et al.* 2010; Hitchman *et al.* 2018).

Less mobile life stages, such as fish eggs and larvae or benthic invertebrates, as well as specialised species – many of which are listed on national Red Lists – are particularly sensitive to hydropeaking (Lubini in Friese *et al.* 2022; Friedrich *et al.* 2024). Judes *et al.* (2023) demonstrate that invertebrate communities are strongly influenced by habitat conditions and their persistence during the two weeks preceding sampling. For adult fish, the persistence of habitat conditions within individual patches appears less critical than their spatio-temporal connectivity: due to their greater mobility, adults can relocate to other patches within the reach where habitat conditions are suitable (Judes *et al.* 2023; Pinter *et al.* 2025). Frequent flow fluctuations can create life-cycle bottlenecks that impair the structure and stability of entire populations over time (Schmutz *et al.* 2015; Kennedy *et al.* 2016; Hayes *et al.* 2025). Thus, habitat dynamics over timescales of days to weeks strongly determine the environmental conditions to which aquatic organisms are exposed (Bätz *et al.* 2023, 2025), with hydropeaking frequency identified as a key driver of habitat variability and connectivity (Chen *et al.* 2026).

Hydropeaking frequency is therefore not merely a hydrological descriptor, but rather a key driver of cumulative ecological impacts whose effects manifests at the patch scale. As synthesised in the conceptual infographic (Figure 4), frequent flow fluctuations alter persistence, temporal availability, and the spatio-temporal connectivity of habitats. These changes affect organisms living within and along the river and may ultimately influence biodiversity, food-web interactions, and ecological functioning at the river-reach scale.

4.3. Spatial differentiation of impacts

Three metrics (M1, M2, M3) recently developed by Bätz *et al.* (2025) quantify habitat dynamics at the patch scale by specifically addressing temporal habitat availability, habitat persistence, and spatial shifts of habitats (Box 1). Together, these metrics enable a spatially explicit assessment of how hydropeaking frequency modifies patch-scale habitat dynamics within a river reach and whether cumulative ecological impacts are evenly distributed or concentrated in specific patches.

Previous approaches have primarily evaluated the effects of hydropeaking based on individual flow fluctuations (Hayes *et al.* 2023). The metrics presented here provide a new and complementary perspective on the cumulative consequences of recurring flow fluctuations on the spatio-temporal dynamics of habitats.

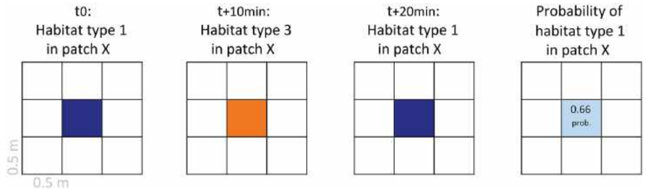
5. CONCLUSIONS

In this article, we synthesise recent empirical and methodological advances to show that the frequency of hydropeaking is a key, yet still underappreciated, driver of ecological impacts, as frequent flow fluctuations can rapidly lead to cumulative losses. Since hydrology interacts with channel morphology to influence habitat dynamics, these impacts are not uniformly distributed throughout a river reach. Instead, they manifest in a spatially differentiated and temporally asynchronous manner at the patch scale – the scale at which ecological processes actually operate. Thus, it is through alterations of patch-scale habitat dynamics that hydropeaking frequency becomes ecologically effective. In this sense, processes operating at the

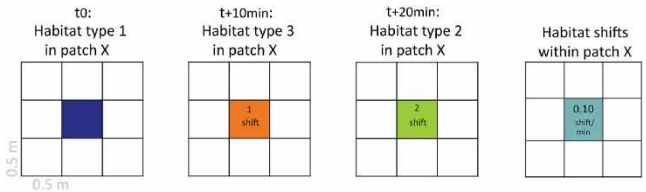
Box 1 | Quantifying patch-scale habitat dynamics using three metrics: M1, M2, and M3

Three metrics developed by Bätz *et al.* (2025) enable the quantification of habitat dynamics under frequent hydropeaking. The metrics capture temporal habitat availability, habitat persistence, and spatial shifts of habitats at the patch scale, thereby directly linking to the ecological mechanisms described in Section 4 and Figure 4. A schematic illustration of the metric calculation (adapted from Bätz *et al.* 2025) and an application example are provided below. Further methodological details and case studies are presented in Bätz *et al.* (2025), Lecrivain *et al.* (2026), and Wittmann (2022). A toolbox can be downloaded from https://github.com/HaDy-toolbox.

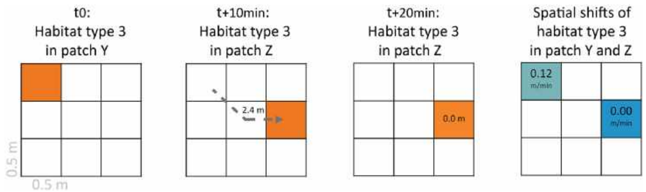
M1 Habitat probability within patches: M1 quantifies the probability of a specific habitat type (e.g. shallow water, low current velocity) occurring within a given patch over a defined period. Therefore, M1 represents the time-integrated availability of specific habitat conditions under dynamic flow regimes.



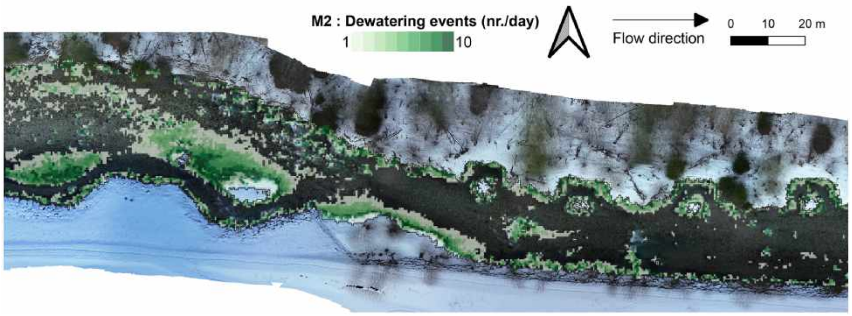
M2 Habitat shifts within patches: M2 quantifies how frequently habitat types change within a given patch. It captures both general shifts between habitat types, as well as specific shifts, such as exposure to dewatering (i.e. stranding) or to elevated current velocities (i.e. drift). Thus, M2 measures habitat persistence, which is particularly relevant for less mobile organisms and early life stages.



M3 Spatial shifts of habitats: M3 quantifies the extent to which habitat types are spatially relocated between patches due to flow fluctuations. Therefore, M3 captures the spatio-temporal connectivity of habitats, which is particularly relevant for mobile organisms that can track their habitats within the mosaic.



Application example (M2): The ecological impacts of hydropeaking frequency are not evenly distributed across a river reach, but rather tend to concentrate in specific patches. M2, like M1 and M3, enables a spatially explicit identification of hotspots of cumulative ecological stress.



patch scale mediate the cumulative ecological impacts of hydropeaking frequency and determine its relevance for ecological mitigation.

The main findings can be summarised as follows:

- **Hydropeaking is highly frequent**: Under hydropeaking, flow fluctuations occur on average three times per day, with only minor seasonal differences. This frequency is 20–60 times higher than under natural flow conditions on an annual basis and 49–78 times higher during spring, an ecologically sensitive period (Figure 2). This high frequency is associated with pronounced cumulative ecological impacts (Figure 1), mediated by mechanisms such as fish stranding and invertebrate drift (Figure 3).
- **Hydropeaking increases habitat dynamics**: High hydropeaking frequency reduces habitat persistence, temporal habitat availability, and the spatio-temporal connectivity of habitats at the patch scale. As a result, the dynamics of the entire habitat mosaic are artificially intensified, affecting organisms living within and along the river through repeated changes in habitat conditions (infographic in Figure 4).
- **Habitat dynamics are measurable**: Three recently developed metrics (M1, M2, M3; Box 1) provide a practical tool to quantify spatio-temporal habitat dynamics at the patch scale. The metrics capture habitat persistence, temporal availability, and spatial shifts of habitats, enabling a spatially differentiated assessment of potential cumulative ecological impacts, for example through fish stranding or invertebrate drift.
- **Spatially explicit mitigation**: Because habitat dynamics and cumulative ecological impacts are not distributed uniformly within a river reach, mitigation measures should be evaluated in a spatially differentiated manner. The three metrics help identify where impacts are concentrated and where mitigation measures are likely to be most effective, without implying fine-scale management of individual patches.

The steps outlined in Table 1 illustrate one possible pathway for integrating patch-scale habitat dynamics into hydropeaking mitigation planning. Their application requires hydrological time series, high-resolution topographic data, and habitat

Table 1 | Integrating patch-scale processes into hydropeaking mitigation

Step	Description
1. Definition of relevant habitats	Specification of habitat conditions that are favourable or potentially critical for the target species and life stages (e.g. shallow water, high current velocity), taking seasonal differences into account. This definition forms the basis for the subsequent calculation of the metrics.
2. Modelling of habitat distribution	Simulation of habitat distribution at relevant discharges (e.g. selected percentiles of the flow-duration curve) using high-resolution topographic data (recommended minimal spatial resolution: ≤1/20 of channel width) to capture the influence of local morphology (e.g. groynes, gravel bars) on patch-scale habitat patterns.
3. Definition of hydrology scenarios	Compilation of high-resolution discharge time series (recommended temporal resolution: 5–15 minutes) representing typical hydropower operational scenarios for ecologically relevant seasons. This includes selecting representative weeks or months under hydropeaking operation as well as defining natural flow conditions for comparison.
4. Derivation of habitat time series and metric calculation	Linking the modelled habitat distributions with the discharge time series to derive habitat time series at the patch scale. Based on these time series, the metrics M1 (habitat probability), M2 (habitat shifts), and M3 (spatial shifts) are calculated for all patches.
5. Identifying spatial patterns	Evaluation of the metrics to delineate areas where elevated habitat dynamics and potential cumulative ecological impacts (e.g. frequent dewatering or high current velocities) are concentrated. These areas should be prioritised when developing and assessing spatially explicit mitigation options.
6. Deriving and evaluating mitigation measures	Mitigation measures are optimised at the river-reach scale and evaluated based on their spatially differentiated ecological effects. The objective is not the fine-scale management of individual patches, but rather the targeted reduction of key cumulative ecological pressures that are spatially concentrated in specific patches.

The steps outlined below illustrate how patch-scale habitat dynamics can be incorporated into hydropeaking mitigation using scenario-based approaches. As with any hydropeaking mitigation, applying this approach requires balancing trade-offs among target species, life stages, and operational constraints. The approach supports a spatially differentiated evaluation of mitigation options at the river-reach scale. Adapted and translated from Bätz *et al.* (2026).

modelling, which are increasingly available through contemporary monitoring and hydraulic modelling approaches. The approach is not intended to prescribe the management of individual patches, but rather to support the identification of areas where cumulative ecological impacts are concentrated and where mitigation measures are likely to be most effective. As with any hydropeaking mitigation strategy, implementation must be adapted to site-specific ecological objectives, regulatory requirements, and operational constraints.

In the context of the energy transition and the growing demand for flexible renewable energy production, the findings presented here clarify the ecological implications of hydropeaking. By identifying the processes through which hydropeaking frequency modifies habitat dynamics, this article provides a scientific basis for more nuanced discussions of ecological trade-offs between energy production and river protection.

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AI DISCLOSURE STATEMENT

To refine this work, the authors used AI tools, such as ChatGPT and DeepL, to check grammar, phrasing and text structure. Subsequent revisions were made to ensure that the final manuscript accurately conveys the intended message and adheres to the standards of scholarly writing.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are derived from previously published sources cited in the manuscript. No new datasets were generated.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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