ENVIRONMENTAL RESEARCH
LETTERS

PERSPECTIVE • OPEN ACCESS

Hydropeaked rivers need attention

To cite this article: R J Batalla *et al* 2021 *Environ. Res. Lett.* **16** 021001

IOP Publishing   *Environ. Res. Lett.* **16** (2021) 021001   https://doi.org/10.1088/1748-9326/abce26

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

PUBLISHED
27 January 2021

PERSPECTIVE

Hydropeaked rivers need attention

R J Batalla[1,2,3], C N Gibbins[4], J Alcázar[1], J Brasington[5], C Buendia[6], C Garcia[7], M Llena[1,8], R López[1], A Palau[1], C Rennie[9], J M Wheaton[10] and D Vericat[1,11]

1 Fluvial Dynamics Research Group RIUS, University of Lleida, Lleida 25198, Catalonia, Spain
2 Catalan Institute for Water Research, Girona 17003, Catalonia, Spain
3 Faculty of Forest Sciences and Natural Resources, Universidad Austral de Chile, Valdivia 5110566, Chile
4 School of Environmental and Geographical Sciences, University of Nottingham—Malaysia Campus, Semenyih 43500, Malaysia
5 Waterways Centre for Freshwater Management, University of Canterbury, University of Lincoln, Christchurch Ōtautahi 8140, New Zealand
6 Alberta Environment and Parks, Environmental Monitoring and Science Division, Edmonton, Canada
7 Department of Geography, University of the Balearic Islands, Palma 07122, Balears, Spain
8 Department of Biological, Geological and Environmental Sciences, University of Bologna, Bologna, Italy
9 Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, Canada
10 Department of Watershed Sciences, Utah State University, Logan, UT 84332-5210, United States of America
11 Forest Sciences Centre of Catalonia Consortium CTFC, Solsona 25280, Catalonia, Spain

E-mail: ramon.batalla@udl.cat

Keywords: hydropeaking, hydro-power, fluvial ecosystems, river sediments, river habitat

Abstract

Hydropower is considered a renewable form of energy production, but generating electricity from rivers is not always environmentally benign. The global demand for renewables is increasing rapidly as fossil fuels are gradually phased out, so rivers will continue to be subjected to the pressures imposed by hydropower for decades to come. Finding ways of operating hydropower plants that limit impacts on downstream river ecosystems is therefore a pressing global concern. Usually, these plants cause marked and rapid fluctuations in flow in downstream river reaches, termed 'hydropeaking'. Hydropeaks result in a variety of ecological changes in the dynamic mountain rivers they typically affect; declines in fish and insect populations are evident, especially in reaches immediately downstream from the plant. While these changes are often acute and readily apparent, the underlying causal mechanisms remain unclear. We argue here that riverbed sediments are a critical but neglected causal link between hydropeaking flow regimes and ecological changes. We outline how a variety of tools from different branches of river science can now be brought together to understand precisely why hydropeaking alters sediment dynamics; these tools provide a mechanistic explanation for changes in bed sedimentary conditions and channel form across multiple scales and, consequently, a better understanding of ecological changes. By allowing us to simulate the effects of flow fluctuations on sediment dynamics and channel form, these tools also allow us to develop ways of releasing water from hydropeaking dams that limit impacts on aquatic habitat and species.

1. Hydropeaking and hydropeaked rivers

Hydropower (HP) is the largest single contributor to renewable energy production globally and currently provides 16% of the world's electricity [1]. While HP plants therefore make an important contribution to green energy production, this can come at the cost of the physical and ecological integrity of downstream rivers [2]. Impacts of HP on river integrity depend on the engineering and operational characteristics of each scheme. Some schemes generate electricity without an impoundment (so called 'run-of-river' schemes), while others rely on dams that impound and release water. Not all HP plants have the same patterns of water release, so their effects on downstream river flows, sediments and ecosystems differ appreciably. The type of operational regime that produces the most unnatural pattern of flow is associated with what are termed 'hydropeaking' dams.

Hydropeaking dams are often relatively small and, to provide the necessary water volumes and water head requirements, are frequently located in

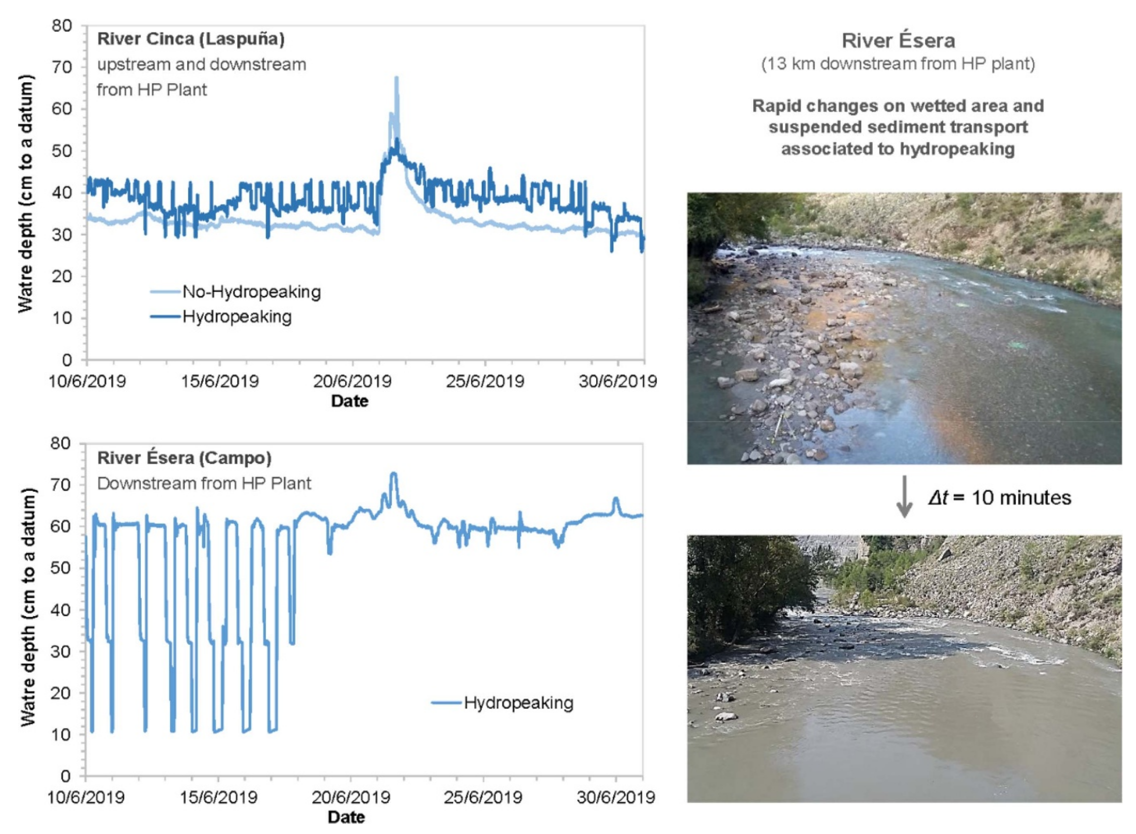

Figure 1. Example of hydropeaking flow regimes from two Pyrenean rivers (Cinca and Ésera). For the Cinca, natural and hydropeaked flow regimes are shown by comparing sites upstream and downstream from the hydropeaking dam. Hydropeaking can increase water depths in the Ésera by up to 50 cm in a few minutes. The photographs illustrate changes in turbidity and water level over a 10 min period in the River Ésera, 13 km downstream from the dam. See table 1 for a description of river attributes affected by hydropeaking.

mountain areas [3]. Consequently, they are common in scenic and otherwise relatively undisturbed mountain valleys. Mountain rivers are very different to the lowland ones which are subjected to other types of HP production—water quality is often very high in mountain rivers, while the steep gradients and high-energy flows, often with strong seasonal variability, form dynamic river channels. These channels have unique and sensitive biological communities evolved to match natural flow seasonality [4] and the habitat mosaic associated with highly active fluvial environments [5].

Hydropeaking involves the release of water coincident with the timing of electricity demand (figure 1). It produces rapid and marked sub-daily fluctuations in discharge in downstream river reaches that can be much greater than natural changes. Discharge fluctuations result in rapid changes in water depth and overall flow hydraulics, along with marked changes in turbidity. Hydraulic changes alter the entrainment and transport of sediments and, in turn, the sedimentary structure of the river-bed [3, 6]. As sediment transport is fundamental in shaping river habitat, over time changes become visibly evident at the river reach scale: for example, the form and arrangement of gravel bars and pool-riffle sequences are altered. Changes in flow and bed habitat affect the population dynamics and diversity of aquatic species [7, 8].

2. Rehabilitation of hydropeaking rivers

A variety of structural, operational and morphological approaches to help minimise impacts of hydropeaking have been developed [9, 10]. *Structural* approaches include re-engineering dams to be able to produce power without releasing water in such unnatural ways. *Operational* approaches involve changing the timing of hydropeaks and/or rates of flow change on the rising and falling limbs of the hydropeaks. These approaches can also include 'hydropeak free-weekends' [11], but as they involve altering the timing or amount of electricity generated, they can affect revenue. *Morphological* approaches involve direct intervention in the river, and may include gravel augmentation to enhance spawning sites for fish, or installation of boulders and deflectors to dissipate energy and provide refugia during hydropeaks. Given the high costs of implementation, investment demands confidence that the adopted approach will have a beneficial effect.

Although there are some exceptions [12] it has been difficult to make mechanistic links between flow changes that occur during hydropeaks and the effects

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

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

[a]Magnitude of the impact depends on the exact nature of the hydropeaking regime, including the difference between peak and minimum flows, rates of change and frequency of peaks.
[b]Relative clarity of the water, acting as a proxy for the concentration of sediments (silt, clay and very fine sands) typically transported in suspension by the water.
[c]Winnowing refers to the selective entrainment of fine particles (sands and gravels) without replacement from upstream, while armouring refers to the development of a coarse surface layer on riverbed. Armoured bed surfaces have larger and well-sorted sediments compared to the subsurface zone.
[d]Topographic shape of the bed offering resistance to the flow to move downslope. Smooth beds are characterised by uniformly relatively small sediments, while rough beds are less sorted having large sediments that protrude further into the water column introducing flow turbulence.
[e]Strength of the channel margins with respect to the forces applied by water flowing downstream.
[f]The width of channel inundated by water.
[g]Impact of hydropeaking on width depends on the magnitude of the difference between peak and low flows, as well as the timing/frequency and rate of change in flow.
[h]Physical attributes and processes interact at multiple rivers scales, maintaining the complexity and diversity of river ecosystems.

of these, integrated over time, on aquatic organisms. This difficulty may arise because few studies have looked at how hydropeaking affects riverbed sediments (figure 2). Although organisms respond directly to flow, they are also influenced indirectly by how flow change affects sedimentary conditions. For instance, invertebrates have been observed to leave the bed and enter the water column during hydropeaking events [13]. This so-called 'drift' could be a direct involuntary response to altered flow hydraulics, but it could be triggered by bed instability or increases in suspended sediment transport, both of which occur during hydropeaks [14]. Over longer timescales, changes in sediment transport alter several fundamental characteristics of the bed (figure 2): the size of sediment present in patches of bed can change, while topographic adjustments occur in response to alterations to patterns of sediment entrainment, transport and deposition (table 1). These changes affect organisms directly and indirectly; for example, sediment size and bed topography influence the movement of water through the bed, with implications for delivery of oxygen to fish eggs and embryos that develop within the subsurface zone. By altering bed roughness and cross-sectional shape, changes to bed sediment size and topography respectively can alter flow hydraulic conditions during hydropeaks, creating feedback. While many studies have demonstrated clear changes to populations of fish and invertebrates in downstream rivers, few have explicitly considered how flow hydraulics in hydropeaking regimes alter sediment dynamics and hence bed conditions [6]; consequently, the exact mechanistic causes of ecological change remain unclear.

This missing sedimentary link is significant from the perspective of rehabilitation, because without knowledge of how proposed operational changes will affect sediment transport, demonstrating their benefits will be difficult. A repeated argument made in ecological studies is that effects of hydropeaking are highly specific (they differ between species and life stages, and from site to site [3]); thus, the rhetoric is that rehabilitation needs to be developed site by site. This appears to undermine hope of being able to develop transferable guidelines. However, by shifting the focus more towards sediment and by taking advantage of emerging data collection, analytical and modelling tools, there is opportunity to develop generic principles to guide dam operation in different rivers.

3. Taking advantage of a new multiscale river science

Recent advances in field data acquisition and processing offer incredible opportunities to study of sediment dynamics and flows in river systems at multiple temporal and spatial scales [15, 16].

Figure 2. Rivers are among the most complex and dynamic systems. They are characterized by transfers of water and sediments that interact to create the habitat used by many species, often at very high densities. As they move seaward, water and sediments connect all river compartments, from the basin headwaters to the lowland deposition zones. River sediments are distributed according to their size and respond to flow hydraulics, creating and maintaining a variety of instream habitats across a range of spatial scales (table 1), and which change naturally over time in response to flow. Organisms have evolved a range of morphological, behavioural and life-history adaptations that allow them to deal with natural changes in flow, so modifying river flows, i.e. their mechanics and temporal variability by building a dam and impounding water alters habitat and compromises the ability of rivers to support their native species.

River sedimentary and topographic data can be acquired from relatively affordable equipment and across large spatial areas but at high resolution. We can now characterise changes in channel planform, topography and channel sedimentology like never before, using many millions of 3D data points across a riverscape (figure 3). Repeated field campaigns allow assessment of the magnitude and nature of changes over time, from the patch (i.e. meter) scale up to the river valley scale (figure 3), and from changes during individual hydropeak events to the cumulative effects of multiple events. Such data can help define valley form and geomorphic setting, and so understand the wider set of controls on fluvial processes (e.g. sediment sources) along with how, as a function of these controls, channels may respond to an imposed hydropeaking regime. Predictive models of fluvial processes, built using the high resolution topographic data, allow design of effective, process-based mitigation measures [17]. For instance, 2D hydraulic and morphodynamic models can be used to understand hydraulics and sediment transport during hydropeaks in different river channel 'types', allowing assessment of how channel configuration reacts to the hydrological regime. These models can therefore be used to understand whether some types of river channel are more sensitive to hydropeaking than others, and simulate the effects of alternative flow regimes on bed conditions.

Data processing tools allow extraction of information from a range of smaller scales within the surveyed area. So how large should this survey area be? The River Styles approach to river characterisation [15, 17] is based on the concept of rivers as nested hierarchical systems, in which characteristics at one scale represent the boundary conditions and dictate the range of behaviours evident at smaller scales. River Styles are defined sections of river that have a characteristic structure, represented using channel geometry, channel planform, and the assemblage of geomorphic units present. Hence, there are different River Styles, each with its associated geomorphic units—floodplains, bars, pools, riffles. Each style emerges as a result of a particular set of valley, geomorphic and flow controls, and each can be expected to respond uniquely (differently to other styles) to changes in the flow regime. Adopting the scale of the River Style therefore provides the basis for an understanding of the implications of hydropeaking that is transferable between sections of the same style, whether in the same or different rivers.

Working at larger scales than this would confound interpretation and prediction of hydropeaking effects as it would effectively incorporate multiple River

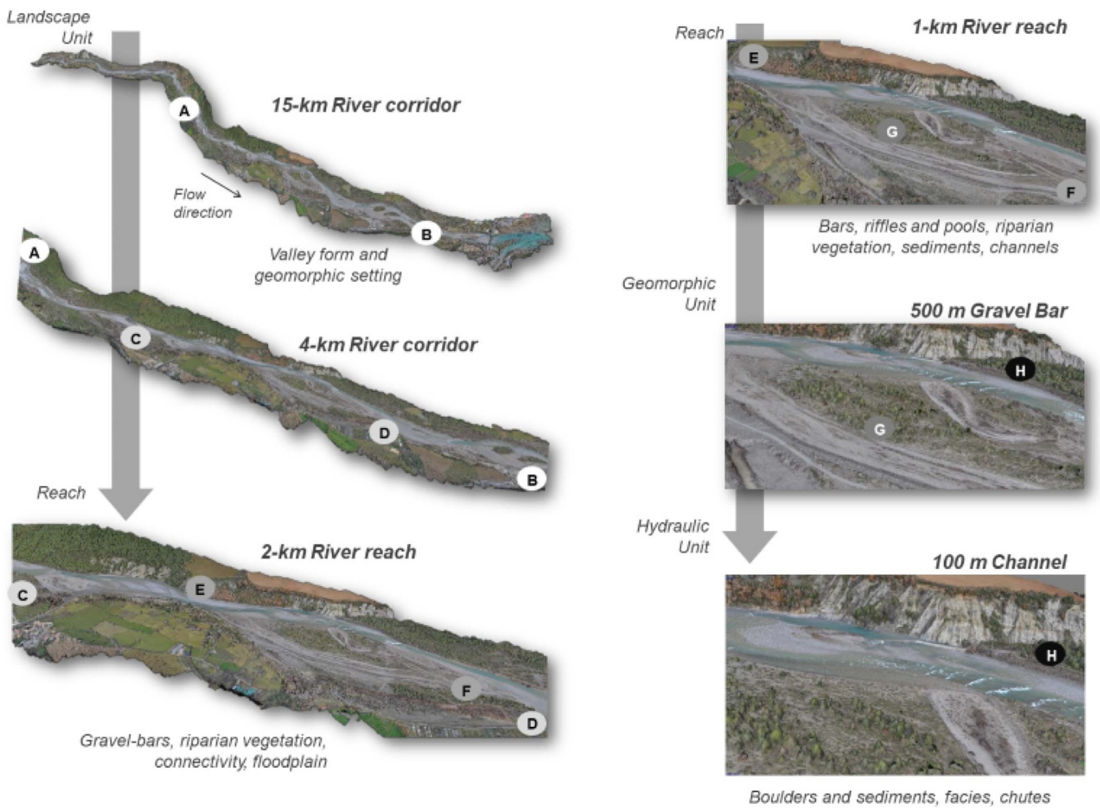

Figure 3. Examples of a 3D point cloud obtained through digital photogrammetry (SfM–MVS algorithms) applied to aerial photographs taken in the River Cinca (South Central Pyrenees). Photographs were collected from an Autogiro flying at an altitude of approximately 200 m from the ground. The point cloud generated for the whole 15 km survey area consists of 240 million data points, each with an *x*, *y* and *z* coordinates. The upper left image shows the whole surveyed area—a 15 km long corridor. The other images show nested parts of the survey area, extracted to show 4 km to 100 m long sections of channel. Different features are apparent at each scale, from the boulders and sediment facies evident in the cloud extracted for the smallest scale, to the distribution of morphological units such as pools and riffles at intermediate scales, up to the valley form and setting evident at the largest scale. Letters tie position across successive images.

Styles into the analysis, each with different characteristics, controls and responses to flow change. Moreover, extending to larger scales would risk conflating different sets of controls on stream ecosystems. This is because over ever-increasing distances along the river continuum, turnover in species composition occurs as a result of factors other than sediment and flow regime (e.g. nutrients, stream temperatures); such larger geographic controls will blur the effects of hydropeaking. Conversely working at finer scales (e.g. an individual morphological unit) not only risks assessments being idiosyncratic but may neglect spatial aspects of habitat that are important for population viability. For instance, the conditions in a riffle may be good for spawning Atlantic salmon *Salmo salar* but multiple riffles are needed to help avoid density dependent effects on post-emergent juvenile fish, while nearby nursery areas with slightly different conditions suited to older juveniles are needed to ensure production of good numbers of smolts [18]. Dispersal and egg deposition can play critical roles in insect population dynamics [19], with flow or sedimentary conditions that impede dispersal and either reduce the presence of or access to suitable conditions for different life stages constraining populations. Working to the River Styles scale ensures that assessments are made at a scale large enough to reflect the area over which populations, rather than individuals, are affected by habitat.

4. Prospects: using river science to support policy

The global expansion of HP brings into sharp focus the need to find less damaging ways of operating existing dams, and to advise on the development of operating rules for new ones. Hydropeaking dams need particular attention, since their operation may result in marked physical and ecological changes in otherwise clean and ecologically important mountain rivers.

A key goal for river science to understand the mechanisms through which flow regimes affect biota, not least because this knowledge can be used to guide flow release programmes for HP plants [20]. The geomorphic and hydrodynamic approaches outlined here help with this goal. Perhaps most importantly, they provide a way of understanding whether some types (Styles) of channel are more sensitive to hydropeaking than others, and how alternative dam release programmes may help limit physical and ecological changes in each Style. The transferability of this understanding will make investment in research and development more palatable to dam operators and attractive to the agencies responsible for river management.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

This work was undertaken and benefited from results and discussions provided in the background of the MorphPeak (Grant No. CGL2016-78874-R) and the MorphHab (Grant No. PID2019-104979RB-I00) projects funded by the Spanish Ministry of Economy and Competiveness, Science and Innovation, and the European Regional Development Fund Scheme. Authors acknowledge the support of the Economy and Knowledge Department of the Catalan Government through the Consolidated Research Group 'Fluvial Dynamics Research Group'—RIUS (Grant No. 2017SGR-0459) and the CERCA Program. Damià Vericat is funded through the Serra Húnter Programme (Catalan Government). We would like to thank the Associate Editor and the two anonymous reviewers for their comments that substantially improved the final version of the manuscript.

ORCID iDs

R J Batalla https://orcid.org/0000-0001-8454-2314
C N Gibbins https://orcid.org/0000-0001-8322-8139
J Alcázar https://orcid.org/0000-0002-1379-6576
J Brasington https://orcid.org/0000-0002-1383-7462
C Buendia https://orcid.org/0000-0001-5966-3202
C Garcia https://orcid.org/0000-0002-4584-9732
M Llena https://orcid.org/0000-0001-7095-6188
R López https://orcid.org/0000-0002-7881-3955
A Palau https://orcid.org/0000-0001-7346-3936
C Rennie https://orcid.org/0000-0003-0683-1932
J M Wheaton https://orcid.org/0000-0002-8361-8150
D Vericat https://orcid.org/0000-0002-5685-4895

References

[1] World Energy Council (available at: www.worldenergy.org/news-views/entry/new-world-energy-council-reporthydropoweras- big-surge-set-to-double-by-2050)
[2] Greimel F *et al* 2018 Hydropeaking impacts and mitigation *Riverine Ecosystem Management* 8, ed S Schmutz and J Sendzimir (Berlin: Springer) 91–110
[3] Waidbacher H, Drexler S S and Meulenbroek P 2018 Danube under pressure: hydropower rules the fish Danube under pressure: hydropower rules the fish *Riverine Ecosystem Management* 8, ed S Schmutz and J Sendzimir (Berlin: Springer) 473–89
[4] Poff N L, Allan J D, Bain M B, Karr J R, Prestegaard K L, Richter B D, Sparks R E and Stromberg J C 1997 The natural flow regime *Bioscience* **47** 769–84
[5] Williams R D, Rennie C D, Brasington J, Hicks D M and Vericat D 2015 Linking the spatial distribution of bed load transport to morphological change during high-flow events in a shallow braided river *J. Geophys. Res. Earth Surf.* **120** 604–22
[6] Vericat D, Ville F, Palau A and Batalla R J 2020 Effects of hydropeaking on bed mobility: evidence from a Pyrenean river *Water* **12** 178
[7] Moog O 1993 Quantification of daily peak hydro-power effects on aquatic fauna and management to minimize environmental impacts *Regu. Riv. Res. Manage.* **8** 5–14
[8] Céréghino R and Lavandier P 1998 Influence of hypolimnetic hydropeaking on the distribution and population dynamics of Ephemeroptera in a mountain stream *Freshw. Biol.* **40** 385–99
[9] Charmasson J and Zinke P 2011 Mitigation measures against hydropeaking effects. A literature review *SINTEF Energy Research* Report Project 12X67351 (Trodheim, Norway)
[10] Moreira M, Hayes D S, Boavida I, Schletterer M, Schmutz S and Pinheiro A 2019 Ecologically-based criteria for hydropeaking mitigation: a review *Sci. Total Environ.* **657** 1508–22
[11] Poff N L and Schmidt J C 2016 How dams can go with the flow *Science* **353** 1099–100
[12] Young P S, Cech J J and Thompson L C 2011 Hydro-power-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs *Rev. Fish Biol. Fish.* **21** 713–31
[13] Schülting L, Feld C K, Zeiringer B, Hudek H and Graf W 2018 Macroinvertebrate drift response to hydropeaking: an experimental approach to assess the effect of varying ramping velocities *Ecohydrology* **12** 1
[14] Béjar M, Gibbins C N, Vericat D and Batalla R J 2017 Effects of suspended sediment transport on invertebrate drift *River Res. Appl.* **33** 1655–66
[15] Fryirs K A, Wheaton J M, Bizzi S, Williams R and Brierley G J 2019 To plug-in or not to plug-in? Geomorphic analysis of rivers using the river styles framework in an era of big data acquisition and automation *Wiley Interdiscip. Rev. Water* **6** e1372
[16] Passalacqua P, Belmont P, Staley D, Simley J and Arrowsmith J R 2015 Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: a review *Earth Sci. Rev.* **148** 174–93
[17] Brierley G and Fryirs K 2018 River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in bega catchment, New South Wales, Australia *Environ. Manage.* **25** 661–79
[18] Malcolm I A, Gibbins C N, Moir H J, Soulsby C and Tetzlaff D 2012 The influence of hydrology and hydraulics on salmonids between spawning and emergence: implications for the management of flows in regulated rivers *Fish. Manage. Ecol.* **19** 464–76
[19] Downes B J and Lancaster J 2018 Itinerant, nomad or invader? A field experiment sheds light on the characteristics of successful dispersers and colonists *Freshw. Biol.* **63** 1394–406
[20] Palmer M and Ruhi A 2019 Linkages between flow regime, biota, and ecosystem processes: implications for river restoration *Science* **365** 1264