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The power of hydropeaking: Trade-offs between flexible hydropower and river ecosystem services in Europe

Terese E. Venus [a,*], Oreoluwa Ola [b], Maria Alp [c], Nico Bätz [d], Maria Dolores Bejarano [e], Isabel Boavida [f], Maria Cristina Bruno [g], Roser Casas-Mulet [h], Mauro Carolli [i], Gabriele Chiogna [j], Marie-Pierre Gosselin [k], Jo H. Halleraker [l], Markus Noack [m], Diego Tonolla [n], Davide Vanzo [o], Daniel S. Hayes [p,*]

[a] *Bioeconomy Economics Research Group, University of Passau, Passau, Germany*
[b] *Governance in International Agribusiness, Technical University of Munich, Germany*
[c] *RiverLy, INRAE, Villeurbanne, France*
[d] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, Kastanienbaum, Switzerland*
[e] *Hidrobiología Research Group, Universidad Politécnica de Madrid, Madrid, Spain*
[f] *CERIS, Civil Engineering Research and Innovation for Sustainability, Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal*
[g] *Research and Innovation Centre, Fondazione Edmund Mach, San Michele all'Adige, Italy*
[h] *Chair of Hydraulic Engineering, TUM School of Engineering and Design, Technical University of Munich, Munich, Germany*
[i] *Energy Systems, SINTEF Energy Research, Trondheim, Norway*
[j] *GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany*
[k] *Department of Aquatic Biodiversity, Norwegian Institute for Nature Research (NINA), Trondheim, Norway*
[l] *Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway*
[m] *Institute of Applied Research, Karlsruhe University of Applied Sciences, Karlsruhe 76133, Baden-Württemberg, Germany*
[n] *Institute of Natural Resource Sciences, Zurich University of Applied Sciences, Wädenswil, Switzerland*
[o] *Institute for Water and Environment (IWU), Karlsruhe Institute for Technology, 76131 Karlsruhe, Germany*
[p] *BOKU University, Department of Ecosystem Management, Climate and Biodiversity, Institute of Hydrobiology and Aquatic Ecosystem Management, Vienna, Austria*

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ABSTRACT

The operational practice of "hydropeaking" allows hydropower plants to cover peaks and deficits in energy demand, but it also impacts river ecosystems. The assessment of hydropeaking impacts plays an important role in safeguarding ecosystem services, but is challenging due to the relative importance of impacts at different sites. To compare impacts in hydropeaking rivers, we elicit expert judgment on the relative impacts of hydropeaking on river ecosystem services. Using the best-worst scaling (BWS) method, we compare the impact on the three categories of river ecosystem services (provisioning, regulating and cultural). Our respondents include 98 hydropower experts. Our analysis accounted for individual heterogeneity to assess how perceptions vary across regions, attitudes and representative river characteristics. We find trade-offs between provisioning and regulating services at the regional and local levels, which represents a key issue in dealing with climate change and ecosystem degradation. The best-affected services were water for power generation, raw materials, water for industrial activities and water for irrigation. The worst-affected services were fisheries and aquaculture, maintenance of population and habitat, and wild animals. Our results have implications for the safeguarding of river ecosystem services and the design of regulatory and incentive schemes for mitigation.

1. Introduction

As international sustainability goals often conflict, solutions require a systematic assessment of the trade-offs involved in different objectives. The concept of ecosystem services offers a framework for measuring trade-offs between society and the rest of nature (Farber et al., 2002), but one of the challenges related to safeguarding of ecosystem services is that they occur on multiple scales (i.e. national, catchment, and local

* Corresponding authors.
E-mail addresses: terese.venus@uni-passau.de (T.E. Venus), daniel.hayes@boku.ac.at (D.S. Hayes).

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landscape units) and such impacts must be understood to optimize societal benefits and ensure long-term resilience (Everard et al., 2014). Given that efforts to optimize the provision of individual services often lead to losses of other services, previous research has suggested that services must be viewed as interrelated bundles and that policies must be developed to consider trade-offs at multiple spatial and temporal scales (Rodríguez et al., 2006).

This tension between sustainability goals is exemplified by hydropower, which represents the world's largest source of renewable energy and contributes significantly to the flexibility of electricity systems (IEA, 2021). However, it can also result in negative impacts on riverine organisms and ecosystems (Baird et al., 2025). The construction of hydropower dams is known to fragment and degrade riverine habitats (Greimel et al., 2018; Hauer et al., 2017; Hayes et al., 2022b; Venus et al., 2020a, 2020b; Venus and Sauer, 2022). Flexible hydropower operation to satisfy peak demands in energy needs can alter the flow regime in rivers (Boavida et al., 2020; Hayes et al., 2023; Reindl et al., 2023). This represents a difficult sustainability trade-off: flexibility through hydropower is essential for a renewable energy transition at the regional, but can damage ecosystems at the local level. Although there is a clear understanding of the general externalities of hydropower (Mattmann et al., 2016), the specific ecosystem service trade-offs in relation to flexible hydropower production is not well understood.

Compared to other energy sources, many hydropower plants can be quickly ramped up and down for the generation of electricity (IEA, 2021), which contributes to complementarity among different variable renewable energy sources (Gonzalez et al., 2023; Pérez Ciria et al., 2020). There are several terms for this type of plants: dispatchable, peaking, or ramping power plants (Fleten et al., 2020; Tarroja et al., 2019). As hydropower is currently the main renewable source capable of stabilizing the energy grid, flexible hydropower production is considered essential for a renewable energy transition (Smokorowski, 2022). This type of flexible operation to cover peaks in demand results in the phenomena called "hydropeaking", which consists of rapid and short-term fluctuations in water flow downstream of hydropower stations (Carolli et al., 2015; Greimel et al., 2016; McManamay et al., 2016). Hydropeaking can also affect fjords, lakes or reservoirs (Halleraker et al., 2022). The term "hydropeaking" can refer to both the operational strategy and impact of intermittent flow ramping from flexible hydropower. Although hydropeaking usually only lasts for several hours, the resulting variation in flows departs from normal hydrological conditions and has impacts on multiple spatial and temporal scales (Carolli et al., 2015; Greimel et al., 2016; Hayes et al., 2022b).

Aside from environmental consequences, the changes in flows from hydropeaking operation can affect the provision of ecosystem services in the downstream and upstream water bodies, especially rivers. Under the ecosystem services framework, rivers provide services related to three categories: (i) provisioning, (ii) regulation and maintenance, and (iii) cultural (Grizzetti et al., 2016). Examples include water supply for industrial, agricultural, hydropower and recreational uses, flood protection, cultural and aesthetic benefits, as well as ecological functions such as the natural purification of water, erosion control, and habitat for many aquatic and terrestrial organisms (Böck et al., 2018; Loomis, 2000). While there is ample evidence that hydropeaking leads to a variety of negative ecological effects in rivers (Alp et al., 2023; Bejarano et al., 2018) and some evidence that hydropeaking can alter the thermal regime (Bakken et al., 2014; Heggenes et al., 2021) as well as affect recreational activities, including white-water rafting (Carolli et al., 2017), angling (Aas and Onstad, 2013; Carolli et al., 2017; Virk et al., 2024), and human safety (Pisaturo et al., 2019), there are fewer comprehensive evaluations of the trade-offs between the different types of ecosystem services that result from hydropeaking (Ruokamo et al., 2024). As assessment is an important task for protecting and prioritizing ecosystem services (Cowling et al., 2008) and the design of incentives (Casas-Mulet et al., 2016; Casas-Mulet et al., 2014; Yu and Xu, 2016), it is necessary to understand the impact of hydropeaking on different services so decision makers can propose strategies to encourage or mandate hydropeaking mitigation.

In the absence of a comprehensive evidence base, it is appropriate to use stakeholder and expert judgment to examine trade-offs, inform decision-making, and set priorities for future research for ecosystem services (de Little et al., 2018). Particularly when facing complex and multi-target decision-making, the Best-Worst Scaling (BWS), a discrete choice survey method underpinned by random utility theory, has been useful for eliciting expert and stakeholder views (Finn and Louviere, 1992). For example, Jones et al. (2013) used BWS in the field of environmental and resource management, to elicit expert and farmer judgment on the effectiveness and practicality of mitigation measures for reducing greenhouse gas emissions from sheep production. Their study identified six priority measures for policy inclusion and noted heterogeneity across farmer-type locality, which suggests a need to account for variation in policy delivery. Similarly, previous research used BWS to identify forest management preferences and priorities of forest owners (Loureiro and Dominguez Arcos, 2012), or to identify stakeholder views on carbon farming practices (Dumbrell et al., 2016), mitigation measures (Glenk et al., 2014), water policy (Wheeler et al., 2017), and producer incentives (Ochieng and Hobbs, 2016). Previous literature has also used BWS to compare trade-offs in ecosystem services, including those related to culture (Kabaya et al., 2020), forests (Bruzzese et al., 2022; Soto et al., 2018), lakes (Tyner and Boyer, 2020), and national parks (Shoji et al., 2021), as the method is well-suited for comparing long lists of items.

In this study, we elicit expert and stakeholder perceptions of the impact of hydropeaking on ecosystem services in affected rivers in Europe using Best-Worst Scaling. In their assessment, the experts used a representative river based on their expertise. In turn, we matched the representative river to additional information about the river reach and catchment area from Grill et al. (2019)'s database on river connectivity, urbanity and water consumption. Our analysis accounts for individual heterogeneity and assesses how perceptions vary across regions and respondent types.

2. The economics and policy of hydropeaking

The flexibility of a hydropower plant depends on its structure (upstream reservoir or run-of-river), head height, turbine types, and operational regimes: (i) run-of-river, (ii) modified run-of-river, (iii) storage (baseload) and (iv) storage (hydropeaking) (Smokorowski, 2022). In the context of flexible energy generation, modified run-of-river and storage facilities used for hydropeaking are most relevant. Modified run-of-river facilities can store small water volumes, offering minimum operational flexibility (Smokorowski, 2022). Storage and large dams can hold vast amounts of water in a reservoir. If plants are operating in hydropeaking mode, turbine operations are matched to power trading, the supply and demand of electricity at the sub-daily level (Harby and Schäffer, 2019).

As an operational practice, hydropeaking is a consequence of a flexible energy generation with both short-term response capability and operating flexibility, and longer zero-flow events (Widén et al., 2021), e.g. in periods of surplus of wind energy. In an energy system, storage hydropower provides power during peak periods while also securing network voltage stability, rapidly reestablishing energy in case of a blackout, and supporting electricity production carry over from high flow to low flow seasons (Román et al., 2019; Tonolla et al., 2017). Hydropeaking is particularly important in energy markets with liberalized electricity generation as hydropower operators are incentivized to adapt their commitment strategies based on different generation scenarios (Román et al., 2019). If peaking hydropower is not available, steam-gas, coal, and gas turbine plants are typically used to cover peak demands (Zhuk et al., 2016). However, these power sources entail significant greenhouse gas emissions. Hence, different strategies for peak shaving (i.e., reducing energy consumption during peak load times) have been proposed (Uddin et al., 2018), including demand side management, the integration of energy storage systems or electric vehicles to grid (Anindito et al., 2019; Uddin et al., 2018).

As hydropeaking can lead to a variety of impacts in rivers, mitigation includes both (i) direct operational (e.g. ramping rate restrictions, environmental flows) and structural (e.g. retention basins, caverns, adjusting hydropower tailrace into lakes) measures as well as (ii) indirect morphological improvements and compensatory actions (e.g., channel restructuring for habitat improvement) (Greimel et al., 2018; Moreira et al., 2019). Recently, the feasibility of hybrid systems, e.g., combining retention basins with battery energy storage systems, has been demonstrated (Höfkes et al., 2024). There has also been research about green hydrogen as a means to decarbonize hard-to-abate sectors and balance variable renewable energy sources (Ruhnau and Schiele, 2023).

Examples of regulations for operational mitigation include ramping rate restrictions to yield a more natural sub-daily flow regime (Moreira et al., 2020). It is recommended that such flow thresholds consider local conditions, including aquatic biota, their life-cycle stages, time of day, and river morphology (Moreira et al., 2019). In Europe, only Switzerland and Austria have legal regulations for hydropeaking flow thresholds, while in the United States and Canada, there is environmental legislation that can require hydropeaking mitigation measures if the impact is deemed high enough (Moreira et al., 2019). Other countries have established special frameworks, such as the water management framework for Western Tyrol in Austria, which establishes ramping rate restrictions during critical times of the year (Reindl et al., 2023). In the EU, other hydropower plants may be encouraged to adopt mitigation through the European Union's taxonomy of sustainable finance, which is obligatory for all major energy companies in the EU/EEA and requires hydropeaking mitigation and environmental flows if the produced electricity is labelled as sustainable (European Commission, 2021). Similarly, as peaking auxiliary services from hydropower are critical to balance the grid and there are few alternatives, several countries define operational restrictions on large storage hydropower plants as they have significant adverse effect upon use (EU Water Framework Directive). In such cases, mitigation must be implemented by other means (European Commission, 2015, 2020). Hydropeaking mitigation tends to be more common for newly granted licenses compared to older ones, but exists on a case-by-case basis in several major hydropower countries, including France, Germany, Norway and Sweden (Kampa, 2022).

Economic research has primarily focused on estimating the costs of operational mitigation measures (e.g., restrictions on flow ramping, timing, frequency and duration of peak releases) related to profits lost by the operators and the need to use alternative sources of electricity (Moreira et al., 2019; Pérez-Díaz and Wilhelmi, 2010; Pragana et al., 2017). They find that targeted peak releases focusing on specific ecological objectives could provide more cost-effective hydropower production than conventional operational rules. Previous research has also modeled the impact of ramping restrictions on a hydropower plant's revenue or profit within different periods, including daily (Pérez-Díaz and Wilhelmi, 2010), five-day (Niu and Insley, 2013), medium-term (Helseth et al., 2023), and annual timeframes (Guisández et al., 2013). In the case of the day-ahead wholesale electricity market (e.g., in Italy, France, Germany, Switzerland, Norway, Sweden, Denmark, California, among others), ramping restrictions were found to result in significant differences between peak and off-peak price (Pérez-Díaz and Wilhelmi, 2010).

Beyond mandatory measures, market-based policy solutions have been proposed, including user-driven or government-driven payments for ecosystem services schemes (Blackman and Woodward, 2010; Vatn, 2010; Yu and Xu, 2016). In the context of alternative operation measures, an example of a user-driven scheme was implemented through "collar" contracts that allow downstream stakeholders to purchase an improved flow regime (Kern and Characklis, 2017). The contract is intended to reduce the annual uncertainty in the cost of ramping restrictions and improve the flow regime from an ecological perspective. In these arrangements, a downstream stakeholder agrees with a third-party insurer; the stakeholder is compensated when the cost is high and requires a payout to the insurer when the costs are low. This should result in net costs that are similar to the long-term mean (Kern and Characklis, 2017). To better understand the societal costs of hydropeaking damages, environmental valuation studies have measured the public's value of different dam operations (Jones et al., 2016), willingness to pay to reduce hydropeaking externalities (Ruokamo et al., 2024), environmental improvements (Kataria, 2009), as well as the construction of fish passes and environmental monitoring (Venus and Sauer, 2022; Venus et al., 2020a, 2020b).

3. Methodology

3.1. Theoretical background

The Best-Worst Scaling approach is underpinned by random utility theory and falls within the family of stated preference methods (Louviere et al., 2015). Random utility theory relies on the assumption that utility is a latent construct that cannot be directly observed by the researcher, but it is possible to explain a portion of consumer utility through a valid preference elicitation procedure (Louviere, 2001). In short, best-worst case scaling presents respondents with repeated choices among a collection of items and asks them to identify the best and worst options from each set.

While choice experiments are especially useful in valuing trade-offs between different attribute and level combinations, the best-worst case scaling method is effective to determining the relative value of options on a scale of importance. There are three cases of best-worst case scaling: the first case (object case), second case (profile case) and the third case (multi-profile case). The third case most closely resembles the traditional discrete choice experiment, whereas the second case (profile) presents respondents with a series of profiles. Each profile contains several attributes and each attribute has multiple levels. From these levels, the respondents must select the best and worst levels (Aizaki and Fogarty, 2019).

3.2. Experimental design

We used the second case (profile case), which uses the structure of profile with several attributes of different levels. For each set, the respondent selects the attribute levels that are best and worst. Compared to rating or ranking many attribute levels, the main benefit of the approach is that it reduces the cognitive burden of the respondent. Similar to a choice experiment, each respondent is shown several cards with different combinations of levels.

An important key to the survey design is the definition of the attributes and levels. To categorize the types of socio-economic effects related to hydropeaking, we use the ecosystem services concept to link the functioning of ecosystems to human welfare (Fisher et al., 2009). The attributes correspond to the three categories of ecosystem services: (i) provisioning, (ii) regulation and maintenance and (iii) cultural (Assessment, 2005; Böck et al., 2018). For each of these categories, we distinguish between two sub-categories to create six attributes each with four levels.

The structure follows Grizzetti et al. (2016), who reviewed and proposed a framework for ecosystem service valuation in fluvial ecosystems. We validated the list of attributes and levels iteratively with expert consultation. To improve comparability to other ecosystem services studies (Hayes et al., 2022a), we included additional categories related to provisioning e.g. wild animals (Hornung et al., 2019) and cultural services (Hermes et al., 2018; Russi et al., 2013). Cultural ecosystem services were the category that needed to be expanded upon as Grizzetti et al. (2016) only distinguished between three categories: recreation, intellectual and aesthetic appreciation and spiritual and symbolic appreciation. We included more detail to reflect different types of active cultural ecosystem services (hiking, boating, angling, bathing) and passive cultural ecosystem services (education, aesthetic appreciation, peace and spiritual appreciation and regional identity (Hermes et al., 2018; Russi et al., 2013). Table 1 shows the final list of ecosystem services arranged by categories (attributes) and specific services (levels).

The combination of the attributes and their levels yields thousands of possible combinations. A fractional factorial design uses only a fraction of the total number of combinations of attributes. While it is possible to use a random selection of combinations, this is often statistically inefficient (Hensher et al., 2015). Thus, there are means to derive a statistically efficient fractional factorial design. We used the JMP® software to construct the design, yielding a D-efficiency of 98.6. The D-efficiency is a function of the geometric mean of the eigenvalues and is a measure of the goodness of the design relative to the hypothetical orthogonal designs (Kuhfeld, 2010). We generated 36 profiles, which were organized into six blocks each with six profiles. Fig. 1 shows an example choice profile. The blocks were randomly assigned to respondents.

3.3. Data collection

We solicited responses through an online survey, which was distributed via emails, professional societies, key regional informants, and social network platforms (Twitter/X, LinkedIn) to hydropower experts and stakeholders (e.g., government, non-governmental organizations, industry, and academia). The survey was distributed through contacts and members of the Hydropeaking Research Network (HyPeak) (Alp et al., 2023) and we encouraged respondents to share the survey widely with their relevant networks. The survey was available in six different languages: English, French, German, Italian, Spanish, and Portuguese. It was open to responses from December 2021 to February 2022. More information about the data collection approach can be found in Hayes et al. (2023).

In the survey, we collected information about each stakeholder's role and specific characteristics related to their experiences and expertise (incl. Countries, discipline, and types of hydropower plants). We included Likert-scale questions about the respondents' opinion on the role of hydropeaking in energy transitions, the necessity of stricter hydropeaking policies, and the concept of free-flowing rivers. Before they assessed hydropeaking impacts on various ecosystem services, we asked the respondents to declare a representative river, which is representative of their experience (incl. Name, country, and hydrological and morphological characteristics). Based on the river information, we matched our data to the global dataset from Grill et al. (2019), which includes indicators for the degree of river connectivity, urbanity and water consumption for the representative rivers and is used in the latent class analysis.

Table 1
Overview of ecosystem services categories (attributes) and their levels (specific services) in rivers.

Types of ecosystem services (Attributes)	Specific services (Levels)
(1) Provisioning: abiotic and biotic materials	Fisheries and aquaculture
	Wild animals
	Raw biotic materials (e.g., algae as fertilizers)
	Raw materials for energy
(2) Provisioning: water uses	Water for drinking
	Water for irrigation
	Water for industrial activities
	Water for power generation
(3) Regulation and maintenance: local scale	Water purification
	Erosion prevention
	Soil formation and composition
	Maintaining populations and habitats
(4) Regulation and maintenance: regional scale	Air quality regulation
	Pest and disease control
	Carbon sequestration (e.g., carbon accumulation in sediments)
	Local climate regulation
(5) Cultural: Recreation (active)	Nearby areas for hiking, running, biking
	Boating
	Angling
	Bathing, swimming
(6) Cultural: Other (passive)	Education and research
	Beauty and landscape
	Peace and spirituality
	Regional identity

3.4. Analysis

Our analysis relies on the discrete choice models and the modelling approach depends on the assumptions about respondent choices. There are three possible approaches: paired, marginal and sequential models (Flynn et al., 2007, 2008; Hensher et al., 2015; Louviere et al., 2015).

We used a marginal sequential BWS model, using Stata (version 17) for analysis, to estimate the expert's selection of the best and worst ecosystem services (ES) impacted by hydropeaking (Marley and Louviere, 2005). In this model, the experts first select the best impacted, then the worst impacted ES. We assume the experts will select the best and then the worst impacted services that satisfies the best-worst choice probability (Marley and Louviere, 2005). This choice probability, represented by a utility parameter U_{ik} for each expert selection i and ES k, consist of a deterministic coefficient β and error term ε. We assume the error term follows a type 1 extreme independent and identically distribution, which allows us to specify conditional logit functional forms for the choice probability models (see eqs. 2, 3 and 7 below).

$$U_{ik} = \beta_{ik} + \varepsilon_{ik} \tag{1}$$

The probability that an ES k_1 is selected as best ES from a choice set containing R alternatives, i.e., other ES, takes a conditional logit form and is represented as:

$$\pi_{isk_1} = \frac{exp[\lambda_1 \beta k_1]}{\Sigma_{r=1}^{R} exp[\lambda_1 \beta_r]} \; s = best\ choice; r = 1, k_1, \ldots, R \tag{2}$$

where β is the estimated coefficient for selecting ES k_1 as the best option. λ_1 is a scale parameter that is typically assumed to be equal to one (Louviere and Eagle, 2006).

The probability that an ES k_2 is selected as best ES from the remaining options in the choice set is represented as:

$$\pi_{isk_2|k_1} = \frac{exp[-\lambda_1 \beta k_2]}{\Sigma_{r \neq 1}^{R} exp[-\lambda_1 \beta_r]} s = worst\ choice \tag{3}$$

The deterministic coefficient β for k_2 is negative i.e., the negative sign in front of the scale parameter since it is selected as the worst impacted ES in the profile. The probability of choosing k_1 and k_2 as the best and worst impacted ES is:

$$\pi_{i,k_1,k_2} = \pi_{i,k_1} \pi_{i,k_2|k_1} \tag{4}$$

We omitted an ES from the model to serve as the reference ES to avoid the multicollinearity trap. Typically, it is recommended to select the attribute with the worst selection as the baseline attribute/level in BWS. As "angling" was the level with one of the worst selections and most interpretable results, it was selected as the baseline category. The choice selections were effects-coded i.e., in 1, 0 and − 1. This ensures the coefficients are uncorrelated with the constant term (Bech and Gyrd-Hansen, 2005) and allows us to estimate a share of preference score for the reference ES (Flynn et al., 2007).

We estimated a share of preference scores from the deterministic coefficient β of each ES to identify their relative importance. The share of preference score for an ES k is estimated as:

$$PS_{k_1} = \frac{exp^{\beta_k}}{\Sigma_{r=1}^{R} exp^{\beta_r}} \tag{5}$$

	Most negatively affected	Most positively affected
Peace and spirituality	☐	☐
Raw materials for energy	☐	☐
Soil formation and composition	☐	☐
Water for irrigation	☐	☐
Local climate regulation	☐	☐
Angling	☐	☐

Fig. 1. Example profile card. Respondents were asked to respond to the following questions: "In your representative hydropeaking river, which ecosystem service is most negatively affected by hydropeaking? Which ecosystem service is most positively affected by hydropeaking?"

SP scores are interpreted as the relative importance between the items and reported in percentage terms to illustrate the extent to which the experts agree on the best and worst affected ES. We cluster the standard errors at the individual level to ensure that we account for potential correlation between the error terms of the choice sets considered by the same respondent.

We interpret the results based on statistical significance, the share of preference scores, coefficients' signs and magnitude. A high share of preference score indicates high consensus, whereas a low score indicates low agreement among respondents. The coefficient's sign indicates a positive or negative effect: the best-affected items have positive coefficients and worst-affected items have a negative coefficient. The magnitude reflects the strength of the effect. Typically, one would expect an attribute with a positive coefficient to have a higher share of preference score and a coefficient with a negative coefficient to have a lower share of preference score. However, it is possible to observe the discrepancy of a positive coefficient with a low share of preference score, which indicates that the attribute is selected as the "best" option relatively infrequently compared to the other options. In most cases, very low percentage scores (close to zero) are negative. This is due to the effects coding (−1, 0 and 1).

Finally, we estimate latent class models to check for selection heterogeneity across experts. Latent class models create homogenous classes for similar choices or selections made by the experts. The probability that two ES k_1 and k_2 are selected as the best and worst impacted ES given C preference classes is:

$$\Sigma_{c=1}^{C}\rho_c\pi_{ir,k_1,k_2|C} = \Sigma_{c=1}^{C}\rho_c\pi_{i,k_1|c}\pi_{ir,k_2|k_1c}\ c = 1,\ldots,C \tag{6}$$

where ρ_{ic} is the probability that an expert selection I belongs to a class c. This probability also takes a conditional logit functional form that simultaneously models choice selections and class membership. Class membership is modeled as a characteristic of the representative river and the expert's opinions on hydropeaking. We focus on the characteristics of the representative river retrieved from the Grill et al. (2019) data including the water consumption index, urbanization index and the river connectivity index. For the individuals, we include opinion variables representing their opinions regarding hydropeaking as a necessary consequence of hydropower, hydropeaking policy and free-flowing rivers. This is specified as:

$$\rho_{ic} = \frac{\left[exp\left(z_i'\gamma_c\right)\right]}{\Sigma_{r=1}^{C=1}\left[exp\left(z_i'\gamma_r\right)\right]} \tag{7}$$

The vector of variables representing class membership, i.e., the characteristics of the reference river and the expert's opinions on hydropeaking, is z_i'. While γ represents the estimated coefficients. To estimate preference heterogeneity, we run the latent class model specified in eq. 7. We estimated a latent class model with three classes. To confirm the robustness of the model and estimated coefficients, we calculated the mean posterior probability of the model to measure how well the model predicts choice behavior and actual choice outcome (Yoo, 2020). We report the SP scores for each class and characterize each class based on the statistically significant class membership covariates.

Differences in scale or error variability can confound model estimates in discrete choice models (Louviere and Eagle, 2006). The scale difference can be caused by contextual, temporal or spatial differences and can lead to biased coefficients. We remedy this by estimating a scale-corrected conditional logit model as a robustness check for the coefficients using the hydrology and morphology characteristics of the representative river and region as scale covariates.[1]

4. Results

4.1. Descriptive statistics

Our sample included 98 respondents. Table 2 shows an overview of respondent characteristics, opinions and experience. From the sample, several types of stakeholders were represented, with most coming from research and government/authority but also including respondents from NGOs, hydropower management, and energy provision. Regarding regional expertise, each respondent was permitted to select up to three countries in which they had worked or researched related to hydropeaking. Within Europe, the most represented countries were Switzerland, Germany, and Austria.

In terms of expertise, the respondents could select multiple disciplines. The majority had expertise in ecology and biology, hydrology and mitigation measures (Table 2). In terms of types of hydropower plants, 69 % had experience with storage plants, 58 % with run-of-the-river plants, 20 % with mini plants (i.e., below 1 MW), 55 % with small plants (1–10 MW) and 68 % with large plants. In the context of river landscapes, 81 % had experience in mountain rivers and 38 % in lowland rivers.

53 % of respondents agreed that hydropeaking is a necessary outcome of flexible energy generation. 73 % agreed that there should be stricter policies for hydropeaking, while slightly less, 58 % of respondents, agreed that rivers should flow freely (Table 2).

In the BWS scaling, the respondents selected a representative river catchment. Table 3 shows the overview of the representative river catchments according to hydrology and morphology.

Further, the representative rivers are depicted in a map at the European scale (Fig. 2). These maps demonstrate a high concentration of representative hydropeaking rivers in Europe, particularly the alpine area, representing the majority of respondents (Table 2).

[1] We do this by assuming that the scale parameter λ_1 in equations 2 and 3 is variable and not equal to one. This variability is then estimated based on contextual, temporal or spatial differences. In this study, we estimate the variability based on the hydrology and morphology characteristics of the reference river and region.

Table 2
Overview of respondent characteristics.

Variable	Percentage
Type of Stakeholder	
Hydropower Manager	9 %
Energy provider	8 %
Government/authority	15 %
NGO	9 %
Research	46 %
Other	12 %
Regional experience	
Scandinavia (Norway, Sweden)	8 %
Western Europe (Spain, Portugal, France)	18 %
Central Europe (Austria, Italy, Germany, Slovenia, Switzerland)	67 %
Others (Turkey, Greece, Lithuania, Belgium, Czech Republic)	6 %
Expertise	
Hydrology	46 %
Physico-chemical properties	7 %
Morphology and sedimentary processes	35 %
Ecology and biology	59 %
Socio-economic topics	6 %
Energy markets	9 %
Policy and regulation	16 %
Mitigation measures	44 %
Other	9 %
Experience with types of hydropower plants	
Storage plants	69 %
Run-of-the-river (RoR) plants	58 %
Mini: <1 MW	20 %
Small: 1–10 MW	55 %
Large: >10 MW	68 %
Experience with river landscapes	
Mountain rivers	81 %
Lowland rivers	38 %
Opinions (% agree or strongly agree)	
Hydropeaking is a necessary outcome of flexible energy generation	53 %
In my country, there should be stricter policies about hydropeaking	73 %
Rivers should flow freely	58 %

Note: Since respondents could select multiple options, the percentages do not add up to 100 %. Values are rounded.

Table 3
Overview of the representative river catchments in terms of hydrology and morphology.

Variable		Percentage
Hydrology	Hydropeaking without minimum flow between peaks (river falls dry between peaks)	2 %
	Hydropeaking with minimum flow allocation between peaks	54 %
	Hydropeaking with seasonally variable flows	44 %
Morphology	Channelized river	46 %
	Near natural single channel river	46 %
	Near natural multi-channel river	8 %

4.2. Best worst scaling

We estimate conditional logit regression models for the attributes, and for their corresponding levels. Table 4 shows the results of the model for the attributes (i.e., categories of ecosystem services).

Relative to regulation and maintenance (regional scale), the best-affected ES attribute is water for provisioning services with a high share of agreement among experts. This includes services such as water for power generation, water for industrial activities, water for irrigation, and raw materials for energy. The worst-affected ES attribute is regulation and maintenance services (local scale), but there is a relatively low share of agreement. Regulation and maintenance (local scale), provisioning (abiotic and biotic materials), and cultural (recreation and other) services are also negatively affected.

Table 5 shows the results of the model for the individual levels (i.e., the degree to which hydropeaking affects specific ecosystem services). It also shows the estimates for sub-sets of the data: responses for the geographic area of Europe. The coefficients in Table 5 are similar to the scale-corrected model's coefficients, in magnitude and significance, lending credence to our results.

The individual best-affected ES were water for power generation followed by raw materials for energy, water for industrial activities, water for irrigation, and air quality regulation (Table 5). The individual worst-affected ES were fisheries and aquaculture, maintenance of population and habitat, and wild animals.

Between the regions, most regions had similar perceptions of the negatively and positively affected ecosystem services. However, we observe some differences between regions in terms of the effects on soil formation and boating. For soil formation, the Scandinavian and Other regions perceived it as negatively affected, but respondents from the Western and Central European regions as positively affected. For boating, the respondents from Scandinavian region perceived it as negatively affected but it was perceived as positively affected in Central Europe.

4.3. Estimating preference heterogeneity

To better understand the factors driving the different understanding of hydropeaking impacts, we estimate a latent class model. The membership variables include the water consumption index of the river, urbanization index of the river, river connectivity index as well as experts' opinions on the necessity of peaking for flexible energy, stricter policies and free flowing rivers.

We find that 69.5 % of the respondents belong to class one (Table 6). This group believe that rivers should flow freely. According to this group, hydropeaking best affects water for power generation (77 %), raw materials for energy (5.8 %) and water for industrial activities (3.9 %). In contrast, the maintenance of populations and habitat, and fisheries and aquaculture are the worst-affected ES, all having share of preference scores of 0 %.

The experts of class two, constituting 14.8 % of the respondents, work with rivers classified by a high urbanization index. Although there was variability in how the experts in this class made selections, most of these selections were not statistically significant. The worst affected ES was water for industrial activities, erosion prevention and pest/disease control. The best affected ES was beauty and landscape.

Class number three is the baseline class, which means the membership variables for classes one and two are interpreted in reference to it. In class three, containing 15.7 % of respondents, the experts select water for power generation, water for irrigation, water for industrial activities and raw materials for energy as the best-affected ES. Furthermore, the experts select soil formation and wild animals as the worst-affected ES.

Overall, class 1 and 3 have stronger statistically significant preferences for certain attributes, but for class 2, the model does not capture strong preferences for many of the given attributes.

5. Discussion

5.1. Trade-offs between types of ecosystem-services

Compared to previous research that focuses on specific types of impacts in one river system, our study offers a holistic comparison of the impacts of hydropeaking on a variety of ecosystem services in many representative rivers.

Our results confirm that there are trade-offs between different kinds of ecosystem services affected by hydropeaking (Bejarano et al., 2018; Böck et al., 2018; Carolli et al., 2017). This aligns with previous research that demonstrates that the optimization of individual services often leads to losses of other services (Rodríguez et al., 2006). Generally, we find that hydropeaking is perceived as positive for regulating services at the regional scale (e.g., enabling flexibility) and for provisioning services related to water use (e.g., power generation), but it negatively

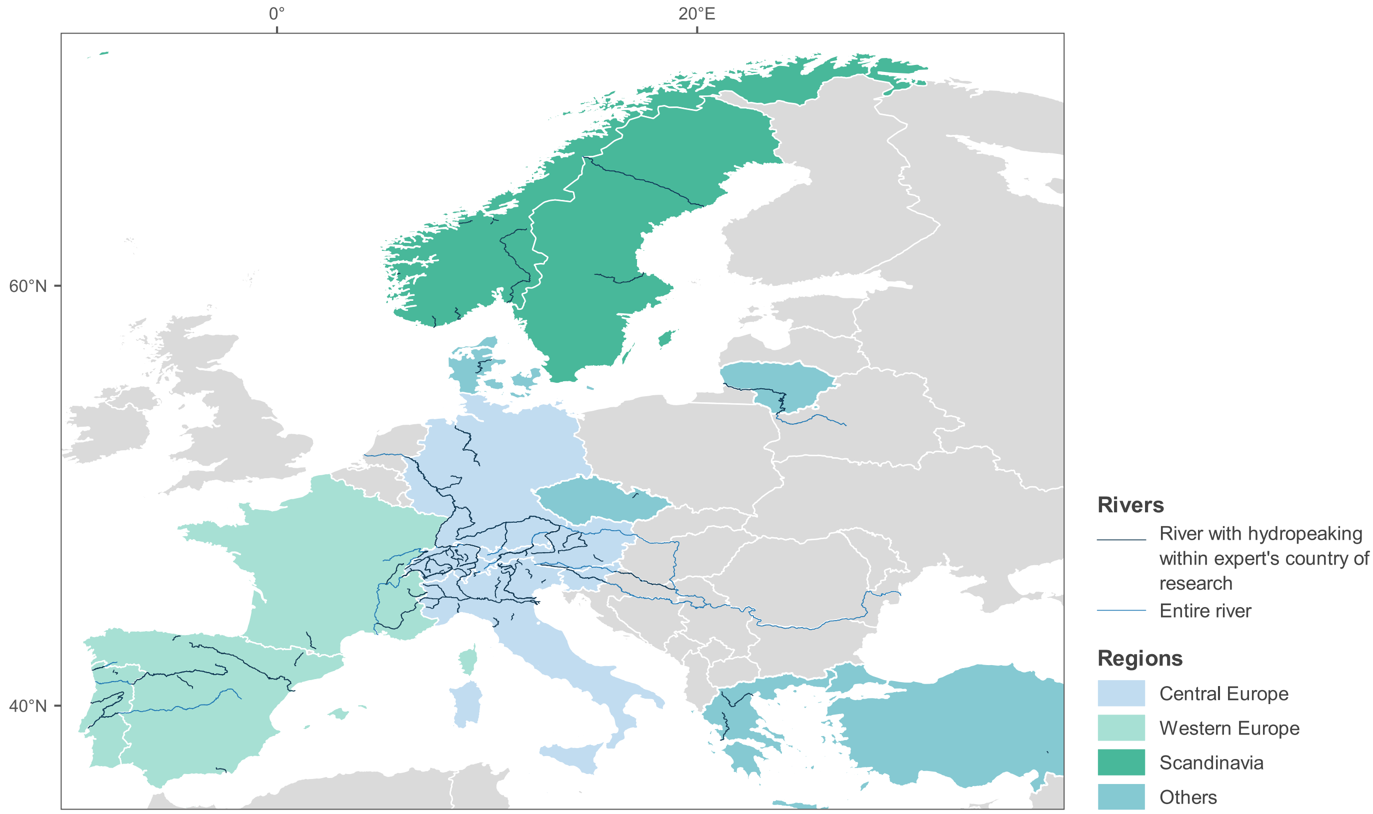

Fig. 2. Representative hydropeaking rivers in Europe covered by the survey.

Table 4
Conditional logit model: Best and worst affected ecosystem services by category.

VARIABLES	Western Europe	SP	Scandinavia	SP	Central Europe	SP	Others	SP
Provisioning: abiotic and biotic materials	−1.596** (0.696)	0.7 %	−2.610*** (0.647)	0.1 %	−2.040*** (0.267)	0.4 %	−3.008*** (0.763)	0.0 %
Provisioning: water uses	3.256*** (0.951)	93.1 %	4.139*** (0.729)	98.1 %	3.526*** (0.384)	92.6 %	4.703*** (0.999)	94.4 %
Regulation and maintenance: local scale	−2.628*** (0.827)	0.3 %	−3.812*** (0.900)	0.0 %	−2.661*** (0.366)	0.2 %	−20.15*** (0.507)	0.0 %
Cultural: Recreation (active)	−1.203 (1.127)	1.1 %	−3.008*** (0.986)	0.1 %	−2.006*** (0.499)	0.4 %	1.681 (1.399)	4.6 %
Cultural: Other (passive)	−1.099 (1.307)	1.2 %	−2.547** (1.071)	0.1 %	0.324 (0.820)	3.8 %	−2.332 (1.828)	0.1 %
Regulation and maintenance: regional scale (baseline)		3.6 %		1.6 %		2.7 %		0.9 %
Observations	918		414		3132		342	

Note: Regulation and maintenance is the baseline level and all coefficients are interpreted in relation to this attribute. Robust standard error in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

affects provisioning services related to abiotic and biotic materials and most of the cultural ecosystem services at the local level. Compared to non-renewables, flexibility through hydropeaking can play a central role in the transition to a cleaner energy system, which can mitigate the effects of climate change. In spite of these benefits, there are harmful potential spillover effects of hydropeaking on the environment, especially on the fauna and flora in the surrounding local environment.

The conflict between the benefits offered by hydropeaking and its potential harmful spillover effects highlights tensions among different types of ES and between the achievement of different Sustainable Development Goals, namely SDG 7 (affordable and clean energy), SDG 6 (clean water including protect and restore water ecosystems) and SDG 15 (life on land including freshwater ecosystems). Our results illustrate this tension in relation to provisioning services. There was consensus among the experts that hydropeaking is positive for ES provisioning services related to water use either for power generation, industrial activities or irrigation. While hydropeaking is perceived as negatively affecting all ES embedded within provisioning services related to abiotic and biotic materials, it is perceived as positive for raw materials for energy in particular. In the policy context, our findings align with the need for further mitigation of hydropeaking as previously noted by Kampa (2022). Although increased attention has been dedicated to hydropower impacts in EU policies, hydropeaking mitigation is still largely missing in most European countries.

5.2. *Trade-offs in costs and benefits at the regional vs. local levels*

Due to the explicit description of which services are realized on the local and regional levels, we find that hydropeaking entails trade-offs between regional and local levels, which represent a key issue when dealing with climate change and ecosystem degradation issues. Specifically, one of the challenges of managing the externalities of greenhouse

Table 5
Conditional logit model: best and worst affected ecosystem services from hydropeaking.

	(1)		(2)		(3)		(4)	
Variables	Western Europe	SP	Scandinavia	SP	Central Europe	SP	Others	SP
Fisheries and aquaculture	−1.045*	0.2 %	−3.130***	0.0 %	−1.060***	0.2 %	−2.275***	0.0 %
	(0.634)		(1.130)		(0.336)		(0.791)	
Raw materials for energy	2.712***	9.3 %	2.800	10.6 %	2.984***	9.4 %	2.707*	0.0 %
	(0.782)		(2.924)		(0.465)		(1.390)	
Raw biotic materials	0.361	0.9 %	−1.407	0.0 %	−0.0516	0.4 %	−1.185**	0.0 %
	(0.606)		(1.220)		(0.280)		(0.470)	
Wild animals	−0.575	0.3 %	−3.242*	0.0 %	−0.827**	0.2 %	−1.440	0.0 %
	(0.832)		(1.967)		(0.365)		(1.326)	
Water for irrigation	1.861*	4.0 %	3.090	14.2 %	1.955***	3.3 %	3.091***	0.0 %
	(1.048)		(2.083)		(0.499)		(0.735)	
Water for power generation	4.377***	49.2 %	4.215*	43.7 %	4.713***	52.7 %	18.84***	100.0 %
	(1.461)		(2.513)		(0.774)		(1.273)	
Water for drinking	1.695*	3.4 %	1.682	3.5 %	1.343***	1.8 %	2.674*	0.0 %
	(0.886)		(1.617)		(0.327)		(1.398)	
Water for industrial activities	2.163***	5.4 %	3.013**	13.1 %	2.702***	7.1 %	3.289**	0.0 %
	(0.706)		(1.438)		(0.408)		(1.323)	
Soil formation / Composition	1.641***	3.2 %	−2.267	0.0 %	0.670*	0.9 %	−2.302**	0.0 %
	(0.618)		(1.533)		(0.403)		(0.912)	
Maintain populations / habitat	−1.822**	0.1 %	−4.582*	0.0 %	−1.323***	0.1 %	−2.229	0.0 %
	(0.717)		(2.491)		(0.443)		(1.780)	
Erosion prevention	0.0144	0.6 %	−1.832	0.0 %	0.715	1.0 %	−1.310	0.0 %
	(0.752)		(1.616)		(0.438)		(1.248)	
Water purification	0.413	0.9 %	0.984	1.7 %	1.034***	1.3 %	−1.198	0.0 %
	(1.006)		(1.422)		(0.394)		(1.008)	
Local climate regulation	0.693	1.2 %	−1.550	0.0 %	1.458***	2.0 %	2.097***	0.0 %
	(0.552)		(1.877)		(0.463)		(0.782)	
Air quality regulation	1.260*	2.2 %	1.408	2.6 %	1.571***	2.3 %	0.615	0.0 %
	(0.644)		(1.895)		(0.324)		(0.688)	
Carbon sequestration	1.686**	3.3 %	−0.708	0.3 %	2.109***	3.9 %	0.407	0.0 %
	(0.776)		(1.180)		(0.518)		(0.701)	
Pest/disease control	1.329**	2.3 %	0.946	1.7 %	1.067***	1.4 %	0.686	0.0 %
	(0.649)		(1.633)		(0.376)		(1.430)	
Bathing/swimming	1.004	1.7 %	−2.280	0.0 %	0.652*	0.9 %	3.513**	0.0 %
	(0.694)		(2.748)		(0.379)		(1.462)	
Boating	1.230	2.1 %	−2.409**	0.1 %	0.979**	1.3 %	0.776	0.0 %
	(1.068)		(1.206)		(0.402)		(0.742)	
Hiking / running	1.161	2.0 %	−0.947	0.3 %	1.694***	2.6 %	0.00283	0.0 %
	(0.838)		(0.667)		(0.457)		(0.447)	
Peace / spirituality	1.038**	1.7 %	−1.800	0.0 %	1.081***	1.4 %	0.630	0.0 %
	(0.514)		(1.310)		(0.317)		(2.660)	
Beauty and landscape	0.00971	0.6 %	−2.835*	0.0 %	0.651	0.9 %	−0.366	0.0 %
	(0.657)		(1.554)		(0.436)		(0.346)	
Regional identity	0.130	0.7 %	−1.499	0.0 %	1.429***	2.0 %	0.709	0.0 %
	(0.523)		(1.682)		(0.438)		(0.596)	
Education and research	1.861*	4.0 %	2.442	7.4 %	1.655***	2.5 %	−0.812	0.0 %
	(1.121)		(1.776)		(0.402)		(1.411)	
Angling		0.6 %		0.6 %		0.5 %		0.0 %
Observations	918		414		3132		342	

Note: Positive coefficients means an ES is best-affected ES, while the worst-affected ES have a negative coefficient. SP refers to the share of preferences and is reported in percentage terms. The percentage values reflect the extent to which the experts agree on the effect of hydropeaking on an ES. If the value is closer to 100 %, it is positively affected. While values closer to 0 %, are often negatively affected. Angling is the baseline level, which means that it represents the reference level to which all other ecosystem services are compared. This means the coefficients should be interpreted in relation to the baseline of angling. Robust standard error in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

gas emissions is the latter are global in their origin and impacts but ecosystems and their related pressures must be managed at the local scale. In the context of hydropeaking, flexible renewable energy results in positive externalities at the continental level, but negative ecological and social externalities at the local level. The geographic issue is particularly relevant when considering who pays and which regulatory tools are used to redistribute the costs and benefits of hydropeaking services. For example, many Austrian hydropower companies sell a considerable share of their generated renewable electricity to Germany, but mitigation is subject to Austrian guidelines (BML, 2024). Within the three categories of hydropeaking mitigation measures (operation, construction and compensation), the "polluter" typically pays for ecological damages while beneficiaries often pay for improving the indirect effects on cultural ecosystem services (Kern and Characklis, 2017).

5.3. *Hydropeaking compared to other hydropower impacts*

In this study, we deliberately focused on the effects of hydropeaking in rivers, with the objective to understand the perception of hydropeaking across stakeholders and experts in relation with ecosystem services. Nevertheless, other positive and negative impacts on ecosystem services should be considered in a wider management perspective. Hydropeaking is primarily associated with high-head storage hydropower systems upstream, which provide load balancing and short-term regulation. At the same time, these may produce cumulative impacts from hydropower development related to storage and result in severe water level fluctuations in hydropeaking reservoirs. Reservoirs themselves can be multipurpose and used for drought mitigation and flood protection (Ward et al., 2020), but the presence of dams can hinder riverine connectivity and have an impact both on biotic communities

Table 6
Latent class model: best and worst affected ecosystem services from hydropeaking.

	(1)		(2)		(3)	
Variables	Class 1	SP	Class 2	SP	Class 3	SP
Fisheries and aquaculture	−1.602***	0.0 %	−1.118	0.8 %	−1.026	0.0 %
	(0.378)		(1.061)		(0.652)	
Raw materials for energy	3.747***	5.8 %	−0.497	1.5 %	1.965***	0.0 %
	(0.352)		(1.043)		(0.707)	
Raw biotic materials	0.173	0.2 %	0.484	4.1 %	−0.698	0.0 %
	(0.325)		(1.255)		(0.595)	
Wild animals	−1.055***	0.0 %	1.281	9.1 %	−1.742***	0.0 %
	(0.342)		(1.222)		(0.654)	
Water for irrigation	2.761***	2.2 %	−1.293	0.7 %	1.699***	0.0 %
	(0.360)		(1.039)		(0.637)	
Water for power generation	6.332***	77.0 %	−0.863	1.1 %	21.48	100.0 %
	(0.651)		(1.109)		(1535)	
Water for drinking	2.028***	1.0 %	−1.186	0.8 %	1.285**	0.0 %
	(0.375)		(1.241)		(0.609)	
Water for industrial activities	3.342***	3.9 %	−2.339**	0.2 %	2.291***	0.0 %
	(0.337)		(1.121)		(0.603)	
Soil formation / composition	1.071***	0.4 %	0.936	6.5 %	−2.101***	0.0 %
	(0.391)		(0.962)		(0.625)	
Maintain populations/habitat	−2.963***	0.0 %	−1.964*	0.4 %	1.840**	0.0 %
	(0.458)		(1.092)		(0.900)	
Erosion prevention	1.126***	0.4 %	−2.199**	0.3 %	−0.898	0.0 %
	(0.368)		(1.076)		(0.660)	
Water purification	1.153***	0.4 %	−1.921*	0.4 %	0.396	0.0 %
	(0.405)		(1.137)		(0.666)	
Local climate regulation	1.885***	0.9 %	−0.174	2.1 %	−0.526	0.0 %
	(0.385)		(1.057)		(0.617)	
Air quality regulation	1.914***	0.9 %	−0.708	1.2 %	0.863	0.0 %
	(0.394)		(1.148)		(0.711)	
Carbon sequestration	2.865***	2.4 %	−0.564	1.4 %	−0.0117	0.0 %
	(0.416)		(1.099)		(0.810)	
Pest/disease control	1.776***	0.8 %	−2.068*	0.3 %	0.0400	0.0 %
	(0.414)		(1.188)		(0.663)	
Bathing / swimming	0.922**	0.3 %	−0.494	1.5 %	0.338	0.0 %
	(0.416)		(1.059)		(0.729)	
Boating	1.643***	0.7 %	−1.017	0.9 %	−0.975	0.0 %
	(0.402)		(1.180)		(0.645)	
Hiking / running	0.877**	0.3 %	2.106	20.8 %	1.375**	0.0 %
	(0.402)		(1.337)		(0.585)	
Peace /spirituality	1.224***	0.5 %	−0.173	2.1 %	0.151	0.0 %
	(0.430)		(0.968)		(0.719)	
Beauty and landscape	0.135	0.2 %	2.647**	35.8 %	−1.117*	0.0 %
	(0.381)		(1.191)		(0.675)	
Regional identity	1.095***	0.4 %	0.0575	2.7 %	0.963	0.0 %
	(0.364)		(1.222)		(0.726)	
Education and research	2.066***	1.1 %	0.000498	2.5 %	1.121	0.0 %
	(0.406)		(1.102)		(0.689)	
Angling (Baseline)		0.1 %		2.5 %		
Class shares	69.5 %		14.8 %		15.7 %	
Opinion: peaking is necessary for flexible energy	−0.359		−0.895			
	(0.490)		(0.678)			
Opinion: stricter policies are needed	−0.221		−0.247			
	(0.362)		(0.530)			
Opinion: rivers should flow freely	−1.076**		−0.666			
	(0.461)		(0.649)			
River connectivity index	0.0299		0.00383			
	(0.0227)		(0.0378)			
Urbanization index of river	0.0823		0.246*			
	(0.111)		(0.141)			
Water consumption index	0.279		0.247			
	(0.255)		(0.270)			
Constant	2.749		1.928			
	(2.682)		(3.968)			
Observations	4554		4554		4554	4554
Number of groups	759		759		759	759

*** p < 0.01, ** p < 0.05, * p < 0.1.
Note: Class 3 is the baseline class; all other classes are interpreted in relation to this class.

and on recreational services. Although not all hydropower plants result in hydropeaking, it may be difficult to separate general impacts (e.g. dams) from hydropower development from the strictly hydropeaking-related impacts.

6. Conclusion

In the context of hydropeaking research, the trade-offs related to ecosystem services are not well understood outside of specific case studies. In this study, we elicit expert and stakeholder perceptions of the impact of hydropeaking on ecosystem services in affected rivers in Europe. In their assessment, the experts refer to a reference river, which we matched to additional information about the river reach and catchment area. In our analysis, we account for individual heterogeneity and assess how perceptions vary across regions and respondent types.

Our results highlight the inherent tradeoff between flexible energy production through hydropeaking (i.e., provision and regulating services) and other ecosystem services. Further, we find that hydropeaking entails trade-offs between regional and local levels, which represents a key issue in dealing with climate change and ecosystem degradation issues. Our study has limitations related to the sample and expertise of the respondents as a majority of respondents work in research. Further, a majority of the respondents work in Central Europe and other areas of Europe could be better represented.

Our results have implications for the safeguarding of river ecosystem services and the future development of payments for ecosystems services schemes. We recommend that decision makers focus their attention on establishing criteria for hydropeaking mitigation, particularly given the growing attention on hydropower mitigation in general. Future research should focus on specific incentive mechanisms for ecologically informed mitigation thresholds (e.g. payments for ecosystem services or collar contracts). Future research should also investigate the cost efficiency of establishing criteria for hydropeaking mitigation related to ecological conditions.

CRediT authorship contribution statement

Terese E. Venus: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Oreoluwa Ola:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Maria Alp:** Writing – review & editing, Methodology. **Nico Bätz:** Writing – review & editing. **Maria Dolores Bejarano:** Writing – review & editing. **Isabel Boavida:** Writing – review & editing. **Maria Cristina Bruno:** Writing – review & editing, Methodology. **Roser Casas-Mulet:** Writing – review & editing, Methodology. **Mauro Carolli:** Writing – review & editing, Conceptualization. **Gabriele Chiogna:** Writing – review & editing. **Marie-Pierre Gosselin:** Writing – review & editing. **Jo H. Halleraker:** Writing – review & editing. **Markus Noack:** Writing – review & editing. **Diego Tonolla:** Writing – review & editing. **Davide Vanzo:** Writing – review & editing. **Daniel S. Hayes:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Terese E. Venus reports financial support was provided by German Ministry of Research and Education. Gabriele Chiogna reports financial support was provided by Deutsche Forschungsgemeinschaft. Daniel S. Hayes reports financial support was provided by Austrian Science Fund. Daniel S. Hayes reports financial support was provided by European Union Horizon 2020. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Appendix

Table A1
Overview of all choice cards by block.

Block	prov_non	prov_use	reg_loc	reg_reg	cul_act	cul_pas
1	Raw materials for energy	Water for irrigation	Soil formation and composition	Local climate regulation	Angling	Peace and spirituality
1	Fisheries	Water for power generation	Maintaining populations and habitats	Air quality regulation	Bathing, swimming	Peace and spirituality
1	Raw (biotic)	Water for drinking	Erosion prevention	Carbon sequestration	Bathing, swimming	Beauty and landscape
1	Wild animals	Water for irrigation	Erosion prevention	Local climate regulation	Boating	Regional identity
1	Raw materials for energy	Water for power generation	Water purification	Pest and disease control	Hiking, running, biking	Beauty and landscape
1	Fisheries	Water for industrial activities	Soil formation and composition	Carbon sequestration	Angling	Education and research
2	Raw materials for energy	Water for industrial activities	Soil formation and composition	Air quality regulation	Boating	Beauty and landscape
2	Raw (biotic)	Water for irrigation	Soil formation and composition	Pest and disease control	Angling	Regional identity
2	Raw (biotic)	Water for industrial activities	Maintaining populations and habitats	Local climate regulation	Angling	Education and research
2	Wild animals	Water for irrigation	Erosion prevention	Carbon sequestration	Hiking, running, biking	Peace and spirituality
2	Fisheries	Water for power generation	Erosion prevention	Pest and disease control	Hiking, running, biking	Beauty and landscape

(continued on next page)

Table A1 (*continued*)

Block	prov_non	prov_use	reg_loc	reg_reg	cul_act	cul_pas
2	Fisheries	Water for drinking	Water purification	Local climate regulation	Bathing, swimming	Regional identity
3	Wild animals	Water for industrial activities	Erosion prevention	Air quality regulation	Angling	Beauty and landscape
3	Raw materials for energy	Water for irrigation	Maintaining populations and habitats	Pest and disease control	Bathing, swimming	Education and research
3	Fisheries	Water for drinking	Soil formation and composition	Carbon sequestration	Boating	Peace and spirituality
3	Wild animals	Water for drinking	Water purification	Pest and disease control	Angling	Beauty and landscape
3	Raw (biotic)	Water for power generation	Soil formation and composition	Air quality regulation	Boating	Regional identity
3	Raw (biotic)	Water for industrial activities	Water purification	Local climate regulation	Hiking, running, biking	Regional identity
4	Fisheries	Water for industrial activities	Maintaining populations and habitats	Pest and disease control	Hiking, running, biking	Regional identity
4	Wild animals	Water for drinking	Soil formation and composition	Air quality regulation	Hiking, running, biking	Education and research
4	Raw (biotic)	Water for power generation	Erosion prevention	Local climate regulation	Angling	Peace and spirituality
4	Wild animals	Water for industrial activities	Water purification	Pest and disease control	Boating	Peace and spirituality
4	Raw materials for energy	Water for power generation	Water purification	Carbon sequestration	Boating	Education and research
4	Fisheries	Water for irrigation	Soil formation and composition	Local climate regulation	Bathing, swimming	Beauty and landscape
5	Raw materials for energy	Water for drinking	Erosion prevention	Air quality regulation	Angling	Regional identity
5	Wild animals	Water for power generation	Maintaining populations and habitats	Carbon sequestration	Angling	Regional identity
5	Fisheries	Water for industrial activities	Erosion prevention	Local climate regulation	Boating	Education and research
5	Raw (biotic)	Water for irrigation	Water purification	Air quality regulation	Hiking, running, biking	Education and research
5	Raw (biotic)	Water for industrial activities	Soil formation and composition	Pest and disease control	Bathing, swimming	Peace and spirituality
5	Wild animals	Water for drinking	Maintaining populations and habitats	Local climate regulation	Boating	Beauty and landscape
6	Raw materials for energy	Water for industrial activities	Erosion prevention	Carbon sequestration	Bathing, swimming	Regional identity
6	Raw (biotic)	Water for drinking	Erosion prevention	Pest and disease control	Boating	Education and research
6	Raw materials for energy	Water for drinking	Maintaining populations and habitats	Local climate regulation	Hiking, running, biking	Peace and spirituality
6	Fisheries	Water for irrigation	Water purification	Air quality regulation	Angling	Peace and spirituality
6	Wild animals	Water for power generation	Soil formation and composition	Local climate regulation	Bathing, swimming	Education and research
6	Raw (biotic)	Water for irrigation	Maintaining populations and habitats	Carbon sequestration	Boating	Beauty and landscape

Questionnaire

Part I. General questions:

1. Stakeholder type
   a. Hydropower manager
   b. Energy provider
   c. Government/authority
   d. Non-governmental organisation (NGO)
   e. Research
   f. Other (please specify)
2. Which countries have you worked or conducted research in? (Selection of up to three countries in drown down menu was possible)
3. What is your area of expertise with regards to hydropeaking?
   a. Hydrology
   b. Physico-chemical properties
   c. Morphology and sedimentary processes
   d. Ecology and biology
   e. Socio-economic aspects
   f. Energy markets
   g. Policy and regulation
   h. Mitigation measures
   i. Other (please specify)
4. What are the conditions of the majority of hydropower plants you manage, work or conduct research on? Type of hydropower plants:

a. Storage
b. Run-of-river

5. What are the conditions of the majority of hydropower plants you manage, work or conduct research on? Size of hydropower plants:
   a. Mini (below 1 MW)
   b. Small (1–10 MW)
   c. Large (above 10 MW)
6. What are the conditions of the majority of hydropower plants you manage, work or conduct research on? Type of river conditions:
   a. Mountain rivers
   b. Lowland rivers
7. Rate the following statement on a scale from 1 to 5 (1 = strongly agree, 5 = strongly disagree): Hydropeaking is a necessary outcome of flexible energy generation.
8. Rate the following statement on a scale from 1 to 5 (1 = strongly agree, 5 = strongly disagree): In my country, there should be stricter policies about hydropeaking.
9. Rate the following statement on a scale from 1 to 5 (1 = strongly agree, 5 = strongly disagree): Rivers should flow freely.

Part II: Research questions (not relevant for this study).
Part III: Impact of hydropeaking.
Please select a reference river representative of your professional experience with hydropeaking.

10. Name of reference river
11. Country of reference river (drop down menu)
12. What are the characteristics of the reference river?
    a. Hydropeaking without minimum flow between peaks (river falls dry between peaks)
    b. Hydropeaking with minimum flow allocation between peaks
    c. Hydropeaking with seasonally variable flows
13. What are the characteristics of the reference river?
    a. Channelized river
    b. Near-natural single-channel river
    c. Near-natural multi-channel river
14. In your reference hydropeaking river, which ecosystem service is most **negatively** affected by hydropeaking? Which ecosystem service is most **positively** affected by hydropeaking? You will see 6 cards.

Example (Block 1).
Card 1

	Most negatively affected	Most positively affected
Raw materials for energy	☐	☐
Water for irrigation	☐	☐
Soil formation and composition	☐	☐
Local climate regulation	☐	☐
Angling	☐	☐
Peace and spirituality	☐	☐
Raw materials for energy	☐	☐

Card 2

	Most negatively affected	Most positively affected
Fisheries	☐	☐
Water for power generation	☐	☐
Maintaining populations and habitats	☐	☐
Air quality regulation	☐	☐
Bathing, swimming	☐	☐
Peace and spirituality	☐	☐
Fisheries	☐	☐

Card 3

	Most negatively affected	Most positively affected
Raw (biotic)	☐	☐
Water for drinking	☐	☐
Erosion prevention	☐	☐
Carbon sequestration	☐	☐
Bathing, swimming	☐	☐
Beauty and landscape	☐	☐
Raw (biotic)	☐	☐

Card 4

	Most negatively affected	Most positively affected
Wild animals	☐	☐
Water for irrigation	☐	☐
Erosion prevention	☐	☐
Local climate regulation	☐	☐
Boating	☐	☐
Regional identity	☐	☐
Wild animals	☐	☐

Card 5

	Most negatively affected	Most positively affected
Raw materials for energy	☐	☐
Water for power generation	☐	☐
Water purification	☐	☐
Pest and disease control	☐	☐
Hiking, running, biking	☐	☐
Beauty and landscape	☐	☐
Raw materials for energy	☐	☐

Card 6

	Most negatively affected	Most positively affected
Fisheries	☐	☐
Water for industrial activities	☐	☐
Soil formation and composition	☐	☐
Carbon sequestration	☐	☐
Angling	☐	☐
Education and research	☐	☐
Fisheries	☐	☐

Data availability

The authors do not have permission to share data.

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