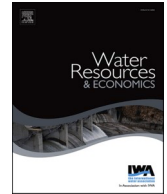




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Impact of environmental flow policy on power system balancing costs and river ecosystem service benefits

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ABSTRACT

Sustainable river regulations require more information on the costs and benefits of environmental flow constraints. This paper presents a case study focusing on the Nordic electricity market and ecosystem service situation. We impose tighter flow ramping constraints on a hydropower plant situated in the Kemijoki River and quantify the effects of the environmental flow policy on hydropower balancing services, river hydraulics and ecosystem services. Our findings reveal that as the environmental flow policy becomes more stringent, the optimal level of balancing market flexibility for the hydropower operator decreases. In addition, a hydrological flow analysis indicates that ecological improvements resulted from the policy. We compare the costs and benefits of the environmental flow policy. The findings indicate that the costs, hydropower revenue loss and increased system balancing costs are comparable to the willingness to pay for environmental improvements. If system balancing can be achieved without an increase in CO₂ emissions, the willingness to pay for the improved river state increases, widening the gap between local benefits and system costs. The study insights can inform policymakers and private companies to better incorporate environmental concerns in the management of regulated rivers while acknowledging the value of hydropower in the power system.

1. Introduction

The REPowerEU plan has proposed increasing the share of renewable energy sources in the EU energy mix by 45 % by 2030, which currently stands at 23 % [1]. Wind and solar energy are promising renewable sources for meeting these ambitious targets. European wind energy capacity grew by 19 GW in 2022 [2]. This change has been even more pronounced in the Nordic countries; for example, in Finland, wind power production increased by 41 % in 2022, covering 14.1 % of electricity consumption [3]. However, wind and solar sources produce intermittent energy, which introduces operational complexities and instabilities into the power system [4]. Moreover, fluctuating electricity prices in energy markets create discrepancies in energy demand and supply, further exacerbating the power system balance [5].

Hydropower is a flexible form of renewable energy generation that provides both baseload and balancing power to accommodate

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these challenges. The ability of hydropower to reserve excess generation capacity during periods of low demand for utilization during peak demand periods allows it to manage changes in overall power generation and provide stability to the energy system [6]. This stability, however, comes at the cost of an operational regime marked by rapid fluctuations in river flow downstream of the hydropower plant (HPP) and is known as hydropeaking [7,8]. Hydropeaking is likely to intensify further in the future because of the increasing amount of intermittent renewable generation.

Multifaceted effects are felt in areas downstream of HPPs engaged in hydropeaking. These effects range from physical effects on the river's hydrodynamics, morphology, and ecology to effects on the overall ecosystem services of the river. This was highlighted in a recent study by Hayes et al. [4], which identified key questions to guide hydropeaking research and policy. The environmental and sociocultural side effects of hydropeaking are, in most cases, externalities that affect different stakeholders for which they are not compensated [9]. These effects are not often accounted for in the optimization of hydropower operations for profit maximization. Regarding negative environmental externalities, hydropeaking causes sudden changes in water levels, velocities, and temperature, negatively affecting invertebrates [10] and fish habitat conditions [11,12]. It also causes erosion, degrading the river's ecological status [13]. In addition, hydropeaking alters flow patterns and therefore may affect diverse recreational services, such as swimming, hiking, boating, and angling [14–16]. Regarding positive environmental externalities, hydropeaking causes lower GHG emissions than most other electricity production forms [17].

The externalities of hydropeaking, positive or negative, can be systematically categorized into different costs incurred or benefits obtained by humans from rivers, utilizing the concept of ecosystem services [18]. In this way, the multifunctionality of rivers can be considered holistically [19]. Ecosystem services are commonly classified as provisioning, regulating and maintenance, or cultural services [18]. For rivers, provisioning services include water provision and fish production for commercial fisheries. The provision services typically have market prices that can be used for their valuation. Regulating and maintenance services include water purification, flood protection, and maintaining populations and habitats. An important cultural service is recreational activities. Regulation, maintenance, and cultural services typically do not have market prices, i.e., they are nonmarket benefits. Overall, hydropeaking causes social, economic, and environmental side effects and influences river ecosystem services and their market and nonmarket benefits.

These effects of hydropeaking should be internalized in the flow allocation decisions of hydropower producers, especially negative externalities. One way to achieve this goal is to have an environmental regulator implement environmental constraints on hydropower operations [20]. Environmental constraints are regulations imposed on hydropower generation to accommodate the needs for other water uses, either consumptive or nonconsumptive. These constraints are incorporated into operational scheduling at HPPs and can include constraints on reservoir levels, downstream releases, river flow and levels, and logical and state-dependent constraints [21]. In run-off-river HPPs, river flow constraints are often imposed to ensure adequate environmental flows (EFs). The EF refers to the quantity and timing of water flows necessary to maintain the functionality of aquatic ecosystems and sustain their associated ecosystem services. The introduction of environmental constraints in hydropower operations can act as a mitigation measure for the abovementioned effects of hydropeaking. When such constraints are integrated into water management practices to alleviate environmental concerns, it is essential to consider their environmental and socioeconomic costs and benefits and implications for electricity production [22]. It is also important to assess the implications of such operating constraints on river hydrology and associated riparian land uses. Thus, a comprehensive evaluation approach is needed that considers all these aspects at multiple scales for resulting hydropower operations [23,24].

The purpose of this study is to holistically assess the effect of an operational hydropeaking mitigation measure on hydropower generation and balancing services, hydrology, and environment via ecosystem services at the reach scale. We compare the monetary costs (lost hydropower revenue and increased system balancing costs) and benefits (willingness to pay estimate with confidence intervals) associated with reduced hydropeaking. Additionally, we conduct a hydrological impact assessment of the hydropeaking mitigation policy.

We contribute to hydropeaking literature as follows. First, we examine how a flow ramping constraint mitigating hydropeaking, henceforth referred to as an EF policy, impacts the operations of a representative HPP engaged in multimarket power generation. We concentrate on the allocation between the day-ahead market and subsequently cleared balancing market. For this purpose, we develop a numeric optimization model of hydropower operations and optimize the model under business as usual (BAU) and moderate improvement in environmental flow (MEFI) scenarios. As a result, we can identify how the total revenues of hydropower generation and system balancing costs change due to the hydropeaking mitigation strategy. Second, we elaborate on the influence of the mitigation strategy by applying hydrodynamic modeling on river hydraulics and in terms of reducing stresses on cultural ecosystem services of the river and its riparian areas. Finally, we assess the monetary value of the environmental outcome of the MEFI scenario by using results from a recent valuation study by Ruokamo et al. [25] and conduct a cost–benefit comparison. Thus, we offer a holistic understanding of the social, economic, and environmental impacts of hydropeaking and how an operational mitigation measure can potentially improve the environmental status of a heavily regulated river. Our analysis focuses on a representative reach below the Osauskoski HPP in the Kemijoki River hydropower cascade in Finland. Although we present context-specific results, we draw novel insights and conclusions on issues considered as a high priority for hydropeaking research and policy development worldwide [4] in large run-of-river systems.

2. Background and related literature

2.1. Case study description

The case study Ossauskoski HPP is located on the Kemijoki River, which is one of the largest and most regulated rivers in Northern Europe and Finland. The river flows through the cities of Sodankylä, Kemijärvi, Rovaniemi, and Kemi all the way to the Gulf of Bothnia, Baltic Sea (Fig. 1). The Kemijoki catchment (50,683 km²) covers a large part of northern Finland. The area contains nine municipalities with approximately 120,000 inhabitants, and the number of households is approximately 61,000 [26].

In 2020, hydropower production in the Kemijoki River covered approximately 6 % of all electricity production in Finland. There are 16 HPPs in the main river channel, and the river is the most regulated river in the country. The studied river reach exists between two HPPs: Ossauskoski (124 MW), the upstream power station, and Taivalkoski (134 MW), the downstream power station (Fig. 1). We assume that the environmental flow policy affects the entire reach between the two power plants, and we scale the benefits accordingly. The effects of upstream HPPs are included in the analysis by using the daily flow profile in the studied river reach. Flow optimization in scenarios is then done at hourly time steps, while adhering to the daily flow constraint. Since the studied hydropeaking mitigation measure does not reduce the amount of water available for turbine operation but only alters the flow allocation profile, we assume that all other factors in the river system, both downstream and upstream of the study reach, remain unchanged across the scenarios.

For a more detailed hydrological impact analysis, a shorter section from Ossauskoski to Tervola is examined (Fig. 1). The studied reach is a representative case of a balancing HPP in the Kemijoki River cascade and its downstream river and riparian ecosystem. The reach is a hydraulically representative reach with its fluvio-morphological characteristics such as sinuosity (1.09), channel slope (0.00065), width to depth ratio (~50) and mean daily flow (596.2 m³/s) similar to those of the overall Kemijoki River (1.64, 0.0009, ~62.5 and 562 m³/s, respectively).

2.2. Hydropower multimarket operation

Hydropower generator in our case study is located in Finland and operates in the Nord Pool electricity market, which spans the Nordic and Baltic regions. The wholesale electricity market is called the day-ahead market (DAM) *Elsport*, where participants submit their schedules a day in advance and market clearing prices for each hour of the following day are determined by the equilibrium points of supply and demand. Balancing services are used on top of the DAM to ensure that the power injections and withdrawals are balanced in the power system [27].

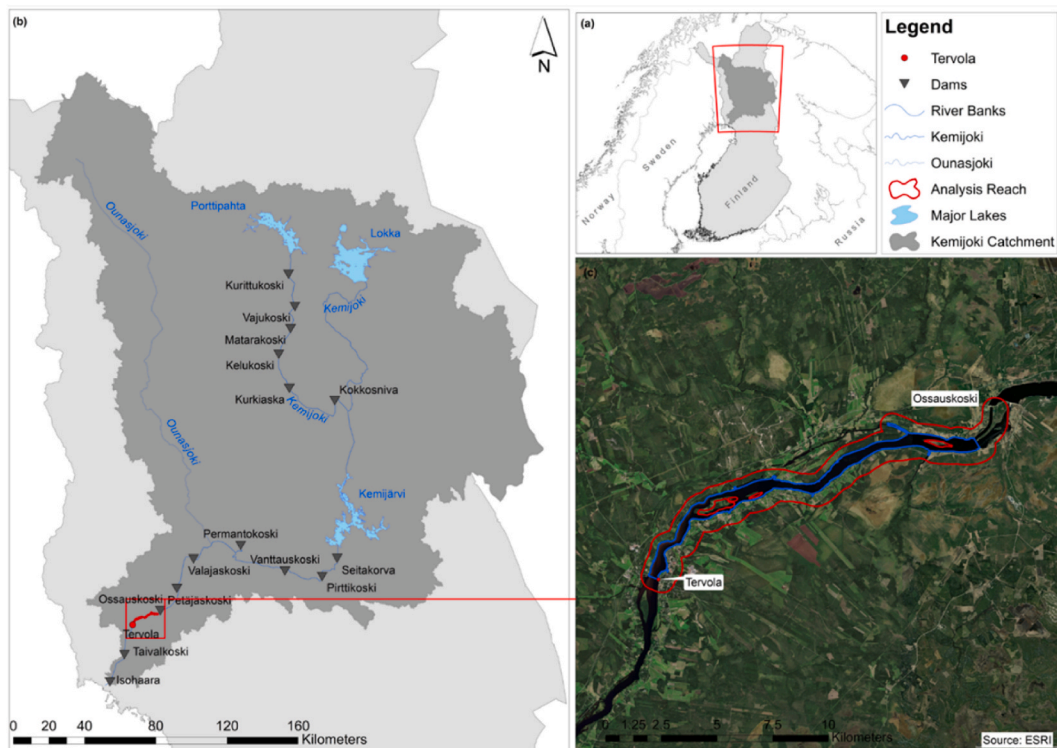


Fig. 1. (a) Finland in the Nordic region, (b) the Kemijoki catchment with its headwaters and major hydropower stations, and (c) the study reach from the Ossauskoski HPP to the town of Tervola.

Hydropower is a major source of power generation in the Nordics, and hydrological conditions impact the price levels of DAM and balancing market (BM) [28]. The opportunity cost of providing balancing services is the revenue loss from the DAM [29]. The electricity producer takes the opportunity cost into account when deciding how much to change the DAM bids given the expected revenue potential from the BM. Coordinated bidding to the DAM and BM leads to higher generation bids at low electricity prices and lower generation bids at high electricity prices, thus increasing the generator's flexibility in offering down- and up-balancing [30].

Given that hydropower operations alter the natural flow regime, tradeoffs are made between the environmental state of the river and the flexibility of hydropower generation. Schillinger et al. [31] divided the impacts of hydropower on natural flows into three levels. The first level is the effect on the natural flow due to the damming and storing of water. The second level is the effect of hydropower operation on flow dynamics, as turbine flow is discharged based on electricity market conditions. The effects of hydropeaking mitigation strategies, i.e., EF constraints on the first and second levels, the reservoir use of HPPs and turbine flow discharge, have been studied extensively [21]. For example, Niu and Insley [32] showed that hydropower ramping restrictions diminish the profitability of hydropower operation. However, over a wide range of ramping restrictions, the reduction in hydropower value is less than 3 %.

The third-level deviation from natural flows is caused by the multimarket operation of hydropower [31]. Overall, the effects of hydropeaking mitigation strategies and EF policies on hydropower multimarket planning have gained less attention in the literature [33]. Schillinger et al. [31] studied the effect of EF boundaries on both single- and multimarket scenarios. Using the German electricity market as a case study, they showed that the loss in revenue due to EF boundaries was greater in multimarket scenarios when boundaries were set according to allowed deviations from natural flow, both on a daily basis and on a monthly basis. Rand [33] explored the effect of the EF for a hydropower project in California. The EF regime reduced the average generation by 6 % but increased the provision of ancillary services such as up- and downregulation services and spinning reserves by 2 %.

Our contribution to the previous literature on multimarket operation is to show how the EF policy constraining flow ramping is internalized in the hydropower profit maximization problem. The optimal level of BM flexibility is determined by equating the opportunity cost in the DAM with the marginal revenue gain in the BM. Importantly, both sides of this optimality condition are influenced by the flow ramp constraint. Thus, it is crucial to model the effect of the flow ramping constraint on both the DAM and BM operations of hydropower plants. In the case study simulation, we examine how the EF policy imposed on the hydropower flow ramping impacts the allocation of hydropower generation between the DAM and subsequently cleared BM.

2.3. Hydrological and associated land-use impacts

As multimarket operations occur at subdaily intervals, downstream river releases from HPPs follow similar patterns, leading to subdaily hydropeaking. Several studies have shown that subdaily hydropeaking significantly alters flow patterns at an hourly resolution [7,8,34,35]. Virk et al. [36] reported that the Kemijoki River falls under the "high pressure class" of subdaily hydropeaking (see Ref. [7] Carolli et al., 2015 for hydropeaking pressure classification) in all seasons from 2010 to 2021. This high degree of subdaily hydropeaking is known to adversely impact riverine ecosystems, ecology, and morphology in multiple ways [37–39], especially in shallow littoral areas adjacent to riverbanks.

Subdaily hydropeaking can have lasting impacts on river morphology [40]. It causes high bank and bed shear stress in the channel, stimulating erosion, affecting bank and bed roughness, and increasing the suspended sediment load [39,40]. It is also the key factor in fish stranding [41] and can severely affect fish breeding habitats. Sudden surges and drawdowns downstream of hydropower plants can cause downstream drift of fish, causing a variety of stresses, including physiological, mechanical, and predatory stresses [42]. Hydropeaking results in variations in water temperature at short intervals, which can affect the reproduction, growth, and survival rate of many fish species [43,44]. It can also affect littoral vegetation, as it affects seed germination and dispersal, plant anchorage, growth, and reproduction in aquatic and riparian plants [38]. In the Kemijoki River, hydropeaking especially impacts on ice formation, fish habitat conditions, recreational possibilities and river bank and bed erosion.

Estimation of these biophysical side effects of hydropeaking relies on accurate modeling of river hydraulic parameters, such as velocity, depth, and shear stress, under dynamic conditions. For instance, spatially distributed water velocity estimates are important for accurately determining fish habitat suitability [45], water depth and velocity are required for estimating the ecological health of rivers [38], shear stress estimates are necessary for determining sediment transport and geomorphological changes in rivers, and surface elevation of river flow is required for hydropeaking-related flooding analyses.

We contribute to the literature by developing a high-resolution hydrodynamic model of the river reach and analyzing the changes in key parameters of river hydraulics, such as water surface elevation, flow velocity, water depth and shear stress, under the BAU and MEFI scenarios. We focus on the hydraulics in the river channel and the littoral zone (the area between riverbanks and high-water marks). Although a large body of literature exists on biophysical impact assessments for hydropeaking, only a handful of studies [4,7,46] have attempted to directly estimate impacts on land use and cultural ecosystem services. The river channel can support a wide array of cultural ecosystem services, such as fishing, swimming, and sunbathing, while the littoral zone can host fixed structures, such as boating decks, summer cottages and saunas. A recent study by Virk et al. [36] estimated the spatial-temporal impacts of short-term hydropower operations in the Kemijoki River and found that all the cultural ecosystem services offered by the river and its littoral zone are threatened by high subdaily hydropeaking. We use outputs from our hydrodynamic model and analyze how these hydrological impacts on cultural ecosystem services can be reduced by implementing an operational mitigation measure, i.e., an EF constraint.

2.4. Ecosystem service valuation

Several valuation methods are available for valuing nonmarket benefits. The choice experiment (CE) method is particularly suitable for situations where several ecosystem services need to be considered simultaneously, such as in hydropower regulation policy. CEs have been used to value river ecosystem services and hydropower externalities in previous studies (see Ref. [9] for a review); however [25], is the only valuation study focusing on hydropeaking.

To calculate the monetary value of the nonmarket benefits associated with the EF policy in the downstream area of the Ossauskoski HPP, we utilized the results of Ruokamo et al. [25]. This study applied a CE to investigate public preferences for policies aiming to reduce hydropeaking in the Kemijoki River. The study area covered the whole Kemijoki River watershed. The valued nonmarket benefits related to the EF policy in the Kemijoki River were recreational use, fish stock, ecological state (quality of habitats, and abundance of benthic flora and fauna), and GHG emissions. Hence, both negative and positive externalities of hydropower operations were considered. In this paper, we first calculate the value of nonmarket benefits and then compare the benefits to the costs associated with the EF policy. To our knowledge, the present study is the first to provide a cost–benefit comparison of hydropeaking regulation.

3. Materials and methods

To holistically assess the effects of hydropeaking and evaluate the performance of our proposed mitigation measure, we applied a combination of methodological approaches. We determined the state of hydropeaking in the Kemijoki River (BAU scenario) and proposed an appropriate mitigation measure (MEFI scenario). To identify the associated impacts of the MEFI scenario, we used three analytical frameworks. First, we developed an optimization model for hydropower operations at the Ossauskoski HPP. The mitigation measure was introduced as an environmental constraint into the optimization model, and the hydropower revenue and system balancing costs were compared under the two scenarios. Second, we examined the hydrological impacts of hydropeaking in the river channel and its riparian areas under the two scenarios. Third, we utilized a recent CE study to estimate the monetary value of changes in river ecosystem services under the MEFI scenario and conducted a cost–benefit comparison. Fig. 2 presents this holistic methodological framework.

The EF policy is presented in Section 3.1. The costs and benefits of the MEFI scenario are quantified in monetary terms based on hydropower analysis (presented in Section 3.2) and ecosystem service value calculation (presented in Section 3.4). The cost assessment

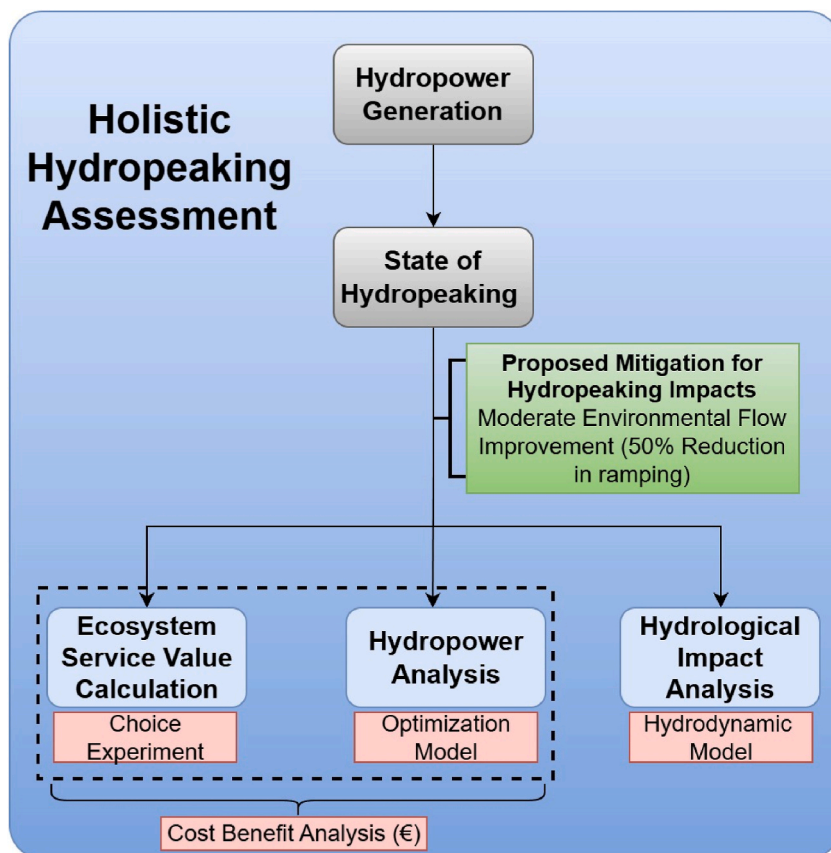


Fig. 2. Framework for holistic analysis of hydropeaking mitigation.

includes reduced hydropower revenue and increased system balancing costs. The benefits are quantified through the willingness to pay of households in the study area. Additionally, a detailed hydrological impact analysis of the MEFI scenario is presented in Section 3.3. These effects provide supplementary information and are not monetized as part of the cost-benefit analysis.

3.1. Proposed hydropeaking mitigation measure

Previous studies on hydropeaking in Kemijoki catchment [5,36,47] have shown that the river is one of the most regulated river in northern Europe with a high hydropeaking pressure at most if not all of its 16 hydropower plants. Subdaily, daily and weekly hydropeaking patterns are observed in the river. One of the key challenges of subdaily hydropeaking is the high ramping rates (rate of change of river flow). The annual median hourly ramping for the Kemijoki River ranged between 125 (m^3/s) and 175 (m^3/s) for the past decade [36]. However, the study also reports significant seasonal variations, with annual median values as high as 200 (m^3/s) in summer and an overall range of 100 (m^3/s) to 400 (m^3/s). Based on the high degree of hydropeaking and consistently high ramping rates we tested the viability of an operational mitigation measure, i.e., reducing the subdaily ramping. As a result of discussions with Kemijoki Oy regarding the current upper limits of ramping rates, we considered the existing hourly ramping rate at 250 (m^3/s). Thus, two scenarios are considered for the following assessments: Business as Usual (BAU) and Moderate Environmental Flow Improvement (MEFI). In the BAU scenario, the hourly ramping rate was set as 250 (m^3/s). In contrast, for the MEFI scenario, under the proposed 50 % reduction in the ramping, a ramping rate of 125 (m^3/s) was considered.

3.2. Hydropower analysis

This section presents the theoretical basis for the numeric hydropower model applied in the analysis. The model describes the DAM and BM operation of a single HPP in the EF policy scenario within the Nordic power market. The hydropower operation model is presented in Appendix A.

For simplicity, assume that the EF parameter is a scalar, $\theta \in \mathbb{R}^1$, describing a one-dimensional hydropower flow restriction. This approach can be applied, for example, to a minimum flow or to a flow ramping constraint of the hydropower turbine flow. We approximate hydropower profit as equal to its operation revenue, as hydropower plants have low variable costs, close to zero [48]. Then, the hydropower operator's problem is to choose the balancing flexibility level, b , so that the total annual operation revenue π (€) from the day-ahead energy market and real-time balancing market is maximized:

$$\pi = \max_b E \left\{ \sum_{d=1}^D [\pi_d^{DAM}(f_d^*(b, \theta)) + \pi_d^{BM}(b, \theta)] \right\}, \quad (1)$$

given the environmental policy constraint θ . The hydropower operator sets the average hourly turbine flow profile f_d (m^3/s) for each hour-of-day to maximize daily revenue from the DAM, denoted as π_d^{DAM} (€). The optimal day-ahead turbine flow allocation for each hour-of-day $h \in \{1, \dots, H = 24\}$ for each day-of-year $d \in \{1, \dots, D = 365\}$ is represented by the vector $f_d^* \in \mathbb{R}^H$. The daily revenue from the BM is denoted by π_d^{BM} (€). Both f_d^* and π_d^{BM} are functions of the balancing flexibility level b and the EF constraint θ .

Both DAM and BM revenues are (weakly) decreasing with respect to the EF constraint θ :

$$\frac{\partial(\pi_d^{DAM}(f_d^*(b, \theta)))}{\partial \theta} = \nabla \pi_d^{DAM}(f_d^*) \cdot \frac{\partial f_d^*(b, \theta)}{\partial \theta} \leq 0, \quad \frac{\partial(\pi_d^{BM}(b, \theta))}{\partial \theta} \leq 0, \quad \forall d \in \{1, \dots, D\} \quad (2)$$

where $\partial f_d^* / \partial \theta = [\partial f_{d,1}^* / \partial \theta, \dots, \partial f_{d,H}^* / \partial \theta]$, $\nabla \pi_d^{DAM}(f_d^*) = [\partial \pi_d^{DAM} / \partial f_{d,1}^*, \dots, \partial \pi_d^{DAM} / \partial f_{d,H}^*]$ and the dot notation (\cdot) refers to the inner product of the two vectors. Both functions are weakly decreasing with respect to θ because for each day d and some value b , the hydropower operator could always have made at least the same revenue from the DAM and BMs before the tightening of the EF constraint θ .

The DAM revenue decreases (weakly) and the BM revenue increases (weakly) with respect to the balancing flexibility level b :

$$\frac{\partial(\pi_d^{DAM}(f_d^*(b, \theta)))}{\partial b} = \nabla \pi_d^{DAM}(f_d^*) \cdot \frac{\partial(f_d^*(b, \theta))}{\partial b} \leq 0, \quad \frac{\partial(\pi_d^{BM}(b, \theta))}{\partial b} \geq 0. \quad (3)$$

where $\partial f_d^* / \partial b = [\partial f_{d,1}^* / \partial b, \dots, \partial f_{d,H}^* / \partial b]$. The DAM revenue decreases (weakly) because more flexibility in balancing operation implies tighter flow restriction for the DAM operation. On the other hand, the BM revenue increases (weakly) because the HPP can offer at least as much balancing services as with a tighter balancing flexibility level. More balancing services imply higher balancing revenue.

The first-order condition for Equation (1) is as follows:

$$E \left\{ \sum_{d=1}^D \left[\frac{\partial(\pi_d^{DAM}(f_d^*(b^*, \theta)))}{\partial b} + \frac{\partial(\pi_d^{BM}(b^*, \theta))}{\partial b} \right] \right\} = 0, \quad (4)$$

where the second derivative must be negative to ensure that b^* maximizes π :

$$E \left\{ \sum_{d=1}^D \left[\nabla^2 \pi_d^{DAM}(f_d^*) \left(\frac{\partial f_d^*(b, \theta)}{\partial b} \right)^2 + \nabla \pi_d^{DAM}(f_d^*) \frac{\partial^2 f_d^*(b, \theta)}{\partial b^2} + \frac{\partial^2 \pi_d^{BM}(b, \theta)}{\partial b^2} \right] \right\} \leq 0. \quad (5)$$

Equation (4) states that the optimal balancing flexibility level b^* is found at a point where the opportunity cost of balancing flexibility, i.e., the revenue loss, in the DAM matches the marginal revenue gain in the BM. In addition, Equation (5) states that the objective function must be concave with respect to b to support a maximum. The importance of modeling the effect of the EF constraint endogenously to the DAM and BM operation decision is highlighted in Equation (6), since the EF parameter θ is present on both sides of the optimality condition:

$$-E \left\{ \sum_{d=1}^D \frac{\partial \pi_d^{DAM}(f_d^*(b^*, \theta))}{\partial b} \right\} = E \left\{ \sum_{d=1}^D \frac{\partial \pi_d^{BM}(b^*, \theta)}{\partial b} \right\}. \quad (6)$$

In the case study, we search for the optimal balancing flexibility level b^* by solving the Ossauskoski hydropower flow dispatch optimization problem in Equation (1) under two scenarios. In the BAU scenario, the EF constraint θ is set to 250.0 (m^3/s). In the moderate environmental flow improvement (MEFI) scenario, the EF constraint is tightened by 50 % to 125.0 (m^3/s).

We model the system balancing price as a function of the HPP's offered balancing quantity (see Appendix A). Accordingly, the system balancing costs differ between the two scenarios. When the HPP's balancing offering in the MEFI scenario is lower (higher) than that in the BAU scenario, we assume that the missing (extra) balancing quantity is ordered from (replaces) the marginal bidder in the balancing supply curve. The price effect of increased (decreased) balancing need is quantified by fitting the balancing price premium, which is the difference between the balancing price and the day-ahead price, with the ordered balancing quantity. Our analysis utilizes balancing market data from 2015 to 2019, corresponding to a total of five balancing year realizations ($Y = 5$).

During an upward balancing hour, more energy (MWh) is needed, $q^{BM} > 0$, and actors with a negative energy balance must purchase the missing energy at an upward balancing price, $p^{BM} > p^{DAM}$ (€/MWh). Then, the system balancing cost (in €) is $q^{BM}(p^{BM} - p^{DAM}) > 0$. During a downward balancing hour, there is too much energy (MWh) $q^{BM} < 0$, and market operators with a positive energy balance must sell the excess energy at a downward balancing price (€/MWh) $p^{BM} < p^{DAM}$ (€/MWh). The balance cost (€) is $q^{BM}(p^{BM} - p^{DAM}) > 0$. The average annual balancing cost for scenario s , BC_s (€), is calculated as follows:

$$BC_s = \frac{\sum_{y=1}^Y \sum_{d=1}^D \sum_{h=1}^H q_{y,d,h}^{BM} (p_{y,d,h,s}^{BM} - p_{h,d}^{DAM})}{Y}, \quad (7)$$

where $q_{y,d,h}^{BM}$ is the balancing quantity (MWh), $p_{y,d,h,s}^{BM}$ is the balancing price (€/MWh), $p_{h,d}^{DAM}$ is the day-ahead wholesale market price of electricity (€/MWh), $h \in \{1, \dots, H = 24\}$ refers to an hour-of-day, $d \in \{1, \dots, D = 365\}$ refers to a day-of-year, $y \in \{1, \dots, Y = 5\}$ refers to a balancing year and $s \in \{BAU, MEFI\}$ is the scenario.

3.3. Hydrological impact analysis

The hydrological impact analysis was carried out by developing a high-resolution hydrodynamic model setup in HEC-RAS 6.3 software. The model was set up for the downstream area of the Ossauskoski HPP by employing a two-dimensional finite element mesh and solving shallow water equations [49]. Geometric data, landcover data for roughness calibration, and observed data for boundary conditions were utilized as key inputs. Manning's roughness coefficient was calibrated manually, with guidelines from Chow and the USGS [50,51]. Calibration and validation were conducted for flow and water depth using data from Finnish Environment Institute (SYKE) and using locally measured water level with pressure sensors. The model's accuracy was evaluated using the coefficient of determination (R-squared). The 2D model simulation provided outputs for the river's hydraulic parameters, such as water surface elevation, water depth, water velocity and shear stress, required for hydropeaking impact assessment. The simulations of the hydrodynamic model were based on the BAU and MEFI scenarios, as described in Section 3.1. The simulation period was designated as a typical summer week for August 2019. The week represents typical regulation practices for both weekdays and the weekend. A more detailed description of the hydrodynamic model setup can be found in Ref. [36].

The reduction in impacts on cultural ecosystem services (CES) was estimated by first identifying CES land use areas. For this purpose, the high-resolution land use and land cover (LULC) map developed by Virk et al. [36] was utilized. The key CES areas included were areas in the littoral zone (beach, summer cottage areas, and riparian forests) and the river channel. The impacted CES areas at subdaily levels were determined by calculating the differences between the maximum and minimum inundation on a Julian day. This vulnerable area representing the affected land parcels was overlaid on a high-resolution (LULC) map. The affected CES areas were calculated through geospatial analyses conducted in ESRI ArcMap software. The spatial resolution of the final outputs matched the LULC map (1 m). Additionally, a 20 m buffer along the stable banks of the reach was delineated to assess the spatiotemporal impacts in the littoral zone.

The suitability of CESs such as swimming, boating, and fishing in the river channel was determined by estimating the hydraulic safety under both the BAU and MEFI scenarios. Hydraulic safety is given as the product of water depth and velocity at any given instance and location in the water body [46,52]:

$$HV_{ij} = Depth_{ij} \cdot Velocity_{ij}, \quad (8)$$

where HV is the hydraulic safety with units as meters squared per second. i is the time datum (hour), and j is the space datum (x, y coordinates). The safety thresholds are defined by Ref. [52], as shown in Table 1.

3.4. Ecosystem service value calculation

A nonmarket valuation study by Ruokamo et al. [25] was utilized to calculate the monetary value of the nonmarket benefits associated with the MEFI policy. The participants of the valuation study were randomly drawn from the civil registry's database. Local individuals were the main target group of the survey. However, a smaller sample of individuals living outside the study area were also invited to participate in the survey to explore the non-use value aspects and whether local preferences differ from the rest of the country. In the end, 82 % of the respondents were locals (i.e., lived in the Kemijoki watershed). Moreover, 10 % of the respondents owned a farm and 18 % owned forest in the watershed area. Thus, the collected sample represented households with varied livelihood strategies and land use practices.

Using the marginal willingness-to-pay values provided by Ref. [25], we first calculated the annual willingness-to-pay per household, \overline{WTP} (€/household per year), for the MEFI scenario with Hanemann's formula [53], $\overline{WTP} = V_1 - V_0$, where V_0 and V_1 are the utility expressions in the WTP space for the BAU and MEFI scenarios, respectively. Improvements in environmental attributes, including recreational use, fish stock and ecological state, were set at a moderate level to correspond to moderate flow restriction (see Ref. [25] for the attribute levels used in the CE). Regarding how the reduced hydropower balancing supply would be compensated in the power system, the valuation of the MEFI scenario was derived under two different assumptions. The first of them represented a situation with the current energy mix where the introduction of EF to hydropower operations increased CO_2 emissions (2 % level) because of additional fossil fuel-based production to balance the power system. The second one related to a potential future situation where the MEFI is implemented assuming emissions-free alternatives substituting the balancing in the power system.

The aggregate WTP (€ per year) for the Ossauskoski area was calculated as follows:

$$WTP = s(\overline{WTP} \cdot N) \quad (9)$$

where N equals the number of households living in the Kemijoki watershed area and s denotes the share of the Ossauskoski-Taivalkoski portion of the Kemijoki River main channel length. Given that the study reach hydraulically represents the whole Kemijoki River (see Section 2.1), we assumed that the Ossauskoski area provides same value of externalities as the Kemijoki River main channel. Furthermore, based on CE-study design in Ruokamo et al. [25], the externalities arising from the modelled hydropeaking mitigation measures are relevant throughout the whole Kemijoki River. In Equation (9), we ignore the potential use and non-use values of residents outside the Kemijoki catchment. Accordingly, the aggregate WTP can be seen as a conservative estimate, based only on the local valuations.

3.5. Cost-benefit analysis

We apply a cost–benefit rule as outlined by Ref. [48]. The rule quantifies the change in societal welfare in monetary units, denoted by dW , resulting from a change in the EF parameter θ . The welfare change is calculated as follows:

$dW = d\pi^F + WTP + dT$, (10) where $d\pi^F < 0$ is the hydropower plant's revenue loss, WTP is calculated according to Equation (9), and dT is the change in taxes. We assume no change in taxes, as there is no alteration in electricity demand or total generation within the model framework. However, we include the change in system balancing costs (according to Equation (7)) under dT , as these costs are paid by all electricity consumers.

We assume the planning costs which are associated with the design of the EF policy are negligible and set them to be zero. The societal welfare analysis in Equation (10) is thus based on annual cost and benefit estimates. Additionally, we conduct a sensitivity analysis of societal welfare using the 95 % confidence interval of the estimated WTP value and. The annual welfare change metric can subsequently be translated into a policy-relevant net present value, enabling consistent comparison across alternative projects or interventions.

4. Results and discussion

In this section we present the results of three assessments based on the theoretical implementation of the EF policy, i.e., the 50 %

Table 1
Hydraulic Safety thresholds.

Degree of Risk	Value of HV (m ² /s)
Low Danger	0–0.5
Moderate Danger	0.5–1
High Danger	1–2
Severe Danger	>2

reduction of hourly ramping (MEFI scenario), and compare the results with the existing ramping regime (BAU scenario). We present and discuss the economic costs incurred by the EF policy in Section 4.1, the hydrological impacts in Section 4.2, and the ecosystem service values with sensitivities in Section 4.3. We compare the estimated costs and benefits at the end of Section 4.3.

4.1. Hydropower energy and balancing services

The results of hydropower optimization show that the total revenue is concave within the optimal balancing flexibility region (see Appendix B). The optimal balancing flexibility level b^* is 25 (m^3/s) in the BAU scenario and 5 (m^3/s) in the MEFI scenario. Given that the EF policy tightens the flow ramp constraint from 250 (m^3/s) to 125 (m^3/s), the hydropower plant chooses to allocate more flow ramping capacity to DAM optimization at the expense of reduced balancing capacity.

The EF policy affects both DAM and BM revenues (Table 2). While the flow ramp constraint does not impact the total DAM generation, it does result in a reduction in revenue per unit of generated hydropower energy. On average, the unit revenue decreases from 46.07 (€/MWh) to 45.66 (€/MWh) as the flow ramp constraint θ tightens from 250 (m^3/s) in the BAU scenario to 125 (m^3/s) in the MEFI scenario. A tighter flow ramp constraint diminishes the hydropower plant's ability to provide balancing services, resulting in a decrease in total revenue from the balancing market. The net effect is that the EF policy reduces total annual revenue by €269,000 (1.12 %) in the MEFI scenario.

The total revenue loss arising from tightened ramping restrictions is consistent with the findings of Niu and Insley [32]. A reduced operational range for turbine flow ramping leads to a decrease in hydropower revenue, but this reduction is only a few percentage points. Most of the revenue loss, approximately 80 %, is associated with a decrease in DAM revenue, while the remaining 20 % represents a loss in BM revenue.

The decrease in balancing energy offered in the MEFI scenario affects the balancing price premiums in upward and downward balancing hours (see Appendix A), as shown in Table 3. On average, the upward balancing price increases by 0.190 (€/MWh), and the downward balancing price decreases by 0.023 (€/MWh) in MEFI. A higher upward balancing price and lower downward balancing price increase the system balancing costs. On average, the annual upward balancing costs increase by €53,000, and the annual downward balancing costs increase by €6000 in MEFI, i.e., the total system balancing costs increase by €59,000.

Our estimate of the increase in system balancing cost in Table 3 is based on the connection between the balancing demand and the balancing price in the BM market from 2015 to 2019. Our approach provides a static estimate of the increase in balancing costs as the available balancing capacity of the HPP decreases. Note that an increase in balancing prices creates revenue opportunities for new resources capable of offering balancing services. This market entry of new resources may result in a lower increase in system balancing costs. These market dynamics were not included in our simulation model.

4.2. Reductions in hydrological impact

Overall, in terms of the reduction in the effects of hydropeaking through the proposed mitigation measure, the total affected area decreased from 2.43 sq km to 2.35 sq km from BAU to MEFI, respectively, out of the total 27.31 sq km of the total analyzed river area (Table 4). In both scenarios, the river channel was the most affected CES area, with only slight differences among the scenarios, as 2.15 and 2.12 sq km out of 8.32 sq km of the total analyzed river channel. Next, riparian forests (0.154 and 0.133 sq km out of 3.37 sq km) and beach areas (0.074 and 0.060 sq km out of 0.21 sq km) were the second and third most affected areas, respectively, under the two scenarios. Most of the improvement was observed in land use proximal to riverbanks within the littoral zone. For example, affected farmland and beach land use areas decreased by 18 %. Summer cottage and riparian forests had 13 % and 14 % reductions, respectively, in the affected area. Here, it is important to understand that channel geomorphology determines the extent to which hydropeaking can affect a river and its services [40]. For a large river such as Kemijoki, a reduction in ramping does not necessarily reduce the hydraulic impacts of peaking in parts of the channel with greater water depth. Hauer et al. [40] assessed hydraulic parameters during peak flows in relation to geomorphological parameters of the river and found that changes in ramping velocities are less correlated with changes in depth of flow (R^2 0.46) than changes in wetted areas (R^2 0.83). This means that a reduction in the ramping

Table 2

Revenue and balancing services in the business-as-usual (BAU) and moderate environmental flow improvement (MEFI) scenarios.

	BAU	MEFI
DAM generation (GWh/a)	521	521
DAM revenue (M€/a)	23.999	23.783
DAM unit revenue ^a (€/MWh)	46.07	45.66
Up-balancing (GWh/a)	3.121	2.180
Down-balancing (GWh/a)	-5.434	-4.143
BM revenue (M€/a)	0.084	0.031
Total revenue (M€/a)	24.083	23.814
Revenue loss (M€/a)	-	-0.269
Revenue loss (%)	-	-1.12

^a Average DAM electricity price: 44.04 (€/MWh).

Table 3

System balancing costs in the business-as-usual (BAU) and moderate environmental flow improvement (MEFI) scenarios.

	BAU	MEFI
Average up-balancing price in up-balancing hour (€/MWh)	62.480	62.670 (+0.190)
Average down-balancing price in down-balancing hour (€/MWh)	33.182	33.159 (−0.023)
Average annual up-balancing cost (M€/a)	5.119	5.172 (+0.053)
Average annual down-balancing cost (M€/a)	2.585	2.591 (+0.006)

Table 4

Areas affected by hydropeaking under the business-as-usual (BAU) scenario and moderate environmental flow improvement (MEFI) scenario, with a 50 % reduction in ramping. Affected land use areas for both scenarios are given in square meters.

Landuse Class	Affected area m ² (BAU)	Affected area m ² (MEFI)	Percentage Reduction
Uncultivated Farmland	16871.3	13810.8	−18 %
Cultivated Farmland	2557.3	2213.8	−13 %
Road	865.3	773.3	−11 %
Non-Riparian Forest	26516.8	24935.3	−6 %
Riparian Forest	153777.0	133283.5	−13 %
Beach	73733.0	60336.0	−18 %
Summer Cottages	2401.3	2069.8	−14 %
Urban Area	445.3	423.8	−5 %
River Channel	2151271.5	2115998.0	−2 %
Total	2428438.5	2353844.0	−3 %

rate will result in greater improvement in shallow areas where changes in depth and velocity of flow are immediately felt. For areas with greater water depth, the increased velocity due to increased ramping under peaked flows affects hydraulic safety (see [Figure B2](#) in [Appendix B](#)).

In addition to determining the overall impact of reduced ramping on land use areas in the reach, we also analyzed the changes in hydraulic properties at various individual analysis points in the river. All of these analysis points were identified in the assumed 20 m littoral zone, as hydropeaking impacts are mostly felt in the river channel or proximal areas. [Fig. 3\(a\)](#) shows seven analysis points in seven sections of the reach. Each of the seven analysis points represents a CES area. Point 1 represents a floating-boat dock immediately downstream of the HPP. Point 2 is located at the downstream end of the first island in the reach and represents a shore area. Point 3 represents a stretch of the riparian forest on the left bank of the reach, point 4 is a private beach, point 5 is a summer cottage area, and points 6 and 7 represent public beach areas.

The analysis in [Fig. 3\(b\)](#) illustrates the hydraulic parameter variations across the different analysis points. Downstream of the HPP at point 1, the BAU scenario exhibits a higher median water depth than the MEFI scenario, but MEFI exhibits slightly greater water velocity, contrary to the expected reduction due to ramping. However, both depth and velocity have wider variations in BAU, suggesting reduced variations in MEFI, potentially decreasing the peak effects on the CES, except for low-depth outliers affecting the floating dock. Points 2 to 6 show similar decreasing trends in depth and velocity under both scenarios, with occasional depth outliers. At point 7, stark differences in hydraulic parameters between BAU and MEFI suggest that the proposed reduction in ramping may mitigate hydropeaking effects further downstream. The water surface elevation decreases downstream from 28.5 to 27.8 m, with outliers occurring at points 3–7 within 20–80 cm of the higher interquartile range for both scenarios. The trend remains consistent, with BAU exhibiting higher elevation than MEFI. Shear stress generally displays equal or higher median values in MEFI across points 1–7, except for a slight reduction at point 2. Although a decrease in water velocity due to reduced ramping should lower the shear stress [40], an opposing trend requires further investigation, especially at point 7. We also investigated the impact of the MEFI scenario on hydraulic safety (see [Appendix B Figure B2](#) for details) and found that a 50 % reduction in ramping did not significantly improve hydraulic safety for recreation. A total of 3.4 % (46327 m²) of the area of the channel was converted to “low” risk, and 0.1 % (2292 m²), 1.2 % (29602 m²) and 1.1 % (25327 m²) reductions were observed in the “moderate”, “high”, and “severe” risk areas, respectively. These results show that although the reduction of high-risk areas to low-risk areas slightly improved, this change was not significant considering the size of the reach. This low improvement in hydraulic safety despite 50 % reduction in ramping can be explained by the fact that the Kemijoki River has been severely disturbed not only due to regulation but also due to dredging carried out by timber industry for log driving from 1860 to 1991 [54].

The proposition of the EF policy as a mitigation measure aims to reduce flow ramping, which eventually results in minimizing variations in water depth, velocity, surface elevation, and shear stress. Stable and consistent flows support river ecosystem services by maintaining uniform conditions throughout the day [55]. Drastic flow changes can severely impact services; for example, rapid changes in water depth can affect beach users or ground a floating dock. The overall impact of changes in hydraulic parameters on CES depends on factors such as bank morphology, service location relative to stable banks, and distance from the HPP [36].

4.3. Ecosystem service values and cost–benefit comparison

The total annual mean willingness to pay per household (\overline{WTP}) of the MEFI scenario combined with the current energy mix in the

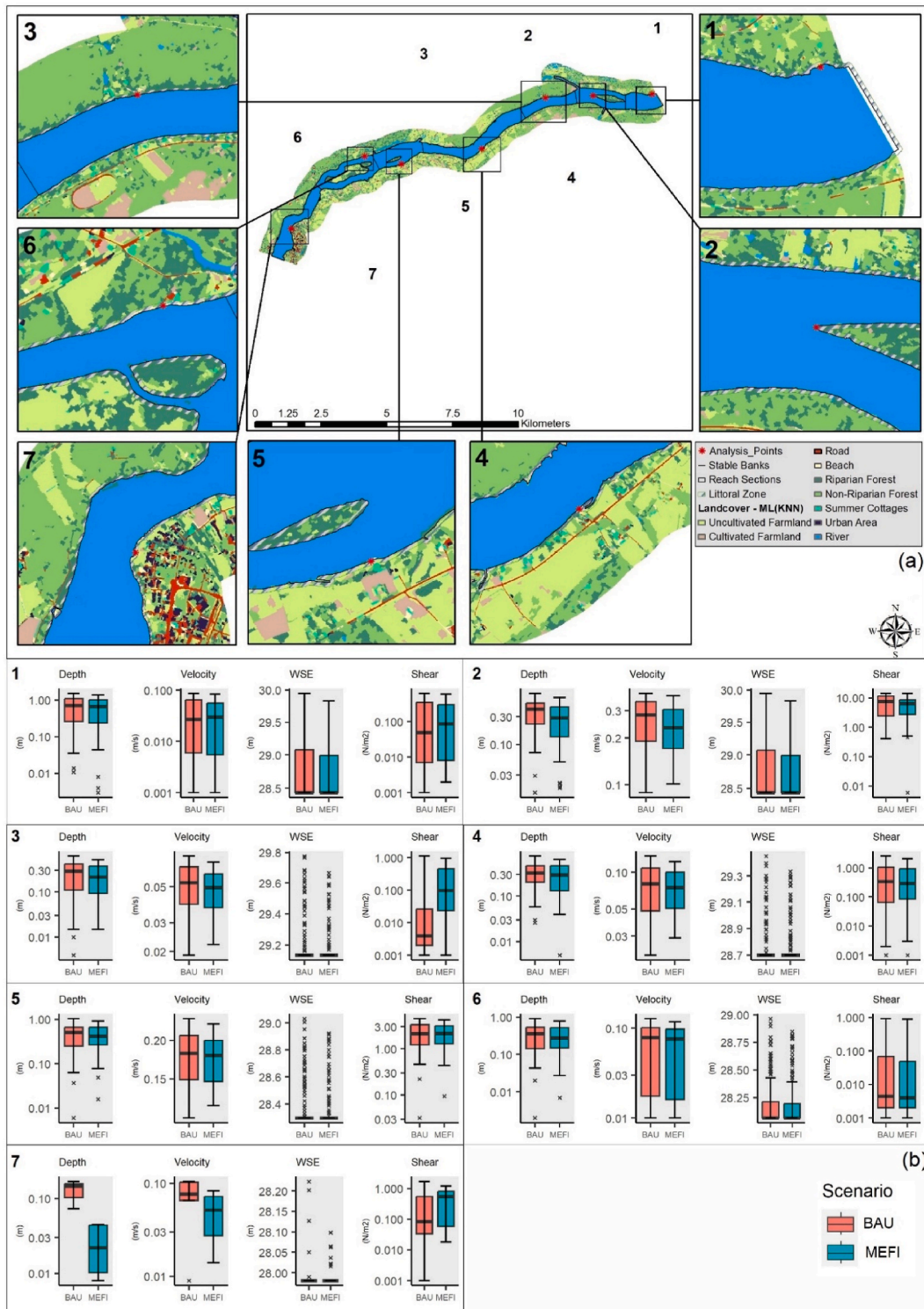


Fig. 3. (a) Analysis points (1–7) representing different recreational services. (b) Variations in hydraulic properties (depth, velocity, water surface elevation, shear stress) at analysis points.

Finnish power system inducing minor increase in emissions was €66.6. The 95 % confidence interval for this was [€16.7 – €116.5]. Note that the valuation of households increased if the required balancing resources, which compensate for the reduced hydropower balancing supply, were provided in an emission-free manner (see Ref. [25]). This corresponded to the total annual mean \bar{WTP} of €92.9

per household in a decarbonized power system. The 95 % confidence interval for this was [€56.4 – €129.3].

These values are in line with the findings of previous studies. For example, Kataria [56] estimated a total willingness-to-pay value of approximately €95 (1100 SEK) per household for a scenario that described an environmental improvement from the current level to the best possible level in a hydropower-regulated river. Our estimates are somewhat lower, but this is expected because we did not consider the best possible outcomes but rather moderate improvements. In addition, Kataria [56] included a wider set of countermeasures for environmental improvement, not just flow restrictions. Furthermore, our study included both negative and positive externalities, in contrast to Ref. [56]. When negative and positive externalities are examined simultaneously, people must consider their tradeoffs, which can lower the total *WTP* value.

Recall that the *WTP* values apply to the Kemijoki River watershed. According to Equation (9), multiplying these values by the number of households ($N = 61,204$) and the share of the Ossauskoski-Taivalkoski portion of the Kemijoki River main channel ($s = 0.082$) leads to an aggregate mean *WTP* value of €334,247 per year for the MEFI scenario with minor increase in emissions for the Ossauskoski power plant. Similarly, an aggregate mean *WTP* value of €466,240 is attained for the MEFI scenario under decarbonized power system.

We present estimates for the welfare changes dW of the MEFI scenario in Table 5. The aggregate mean *WTP* for the MEFI scenario with minor increase in emissions slightly exceeds the estimated costs, including hydropower revenue loss ($d\pi^F$) and the increase in system balancing costs (dT), resulting in a positive welfare change of €6247 per year. The aggregate mean *WTP* for the decarbonized power system is presented in the second column. When system balancing is addressed without increases in emissions, the benefits of the MEFI scenario clearly outweigh the estimated costs, resulting in an annual welfare change of €138,240.

When considering the most conservative benefit estimates (i.e., the lower bound of the 95 % confidence interval around the mean *WTP*), the MEFI scenario yields a negative welfare change for both minor increase and no increase in emissions. On the other hand, the upper bound *WTP* estimates produce significant positive welfare changes.

The results shown in Table 5 should be interpreted with caution because transferring the results of the original valuation study focusing on the whole Kemijoki River watershed, which includes multiple HPPs, to a single HPP along the same river is not straightforward. We assumed that the *WTP* values could be transferred to the Ossauskoski HPP based on its share of kilometers in the Kemijoki River main channel. Alternatively, aggregate valuation could be performed by utilizing a distance decay function [57]. However, in Ref. [25], distance was not a significant variable for explaining preferences or valuations, indicating that nonuse values were important along with use values for the local people living in the Kemijoki River watershed area. These findings support the approach applied in our study. In addition, our approach using watershed scale valuation estimates aligns with Hanley et al. [58]. They suggest that to reduce part-whole bias when aggregating nonuse values, it is better to use valuation estimates for regional projects (such as at the Kemijoki watershed scale) rather than for more localized ones (such as at the Ossauskoski reach scale). This may help mitigate the risk of overestimating total nonuse values due to overlapping valuations across smaller, localized reach areas.

To enable meaningful project comparisons, the annual changes in welfare presented in Table 5 can be translated into a net present value (NPV) using discounting [48]. By applying a discount factor of $\beta = \frac{1}{(1+r)}$, where the discount rate satisfies $0 < r < 1$, the NPV is calculated as the discounted sum of future welfare changes: $NPV = \sum_{t=0}^T \beta^t dW$. Assuming a long-term horizon where $T \rightarrow \infty$, the NPV converges to $\frac{dW(1+r)}{r}$. There is no single consensus value for the social discount rate. However, using discount rates in the range of 0.03–0.05 (see Refs. [48,59]) yields NPV values of approximately 34 dW and 21 dW , respectively.

5. Conclusions and policy implications

By exploring the impact of hydropeaking constraints on hydropower revenue, balancing market prices, and ecosystem services of a river, our study contributes to a comprehensive understanding of the complexities involved in assessing optimal hydropower environmental flow constraints.

We show that hydropower operators reduce their balancing capacity within the Nordic power markets due to the environmental flow policy targeted to mitigate hydropeaking. The findings indicate that both the day-ahead market and the balancing revenues of the hydropower operator decrease. In addition, the system balance costs increase. Thus, the environmental flow policy has negative effects on hydropower production and power systems. However, the policy positively influences river hydraulics and associated ecosystem services. We find that there is a slight reduction in the total affected area and significant improvement in the shallow areas of the littoral zone when the ramping constraint is implemented. Moreover, the environmental flow constraint reduces fluctuations in hydraulic parameters in downstream parts of the reach, indicating a stable flow regime, which is a desirable hydraulic state. This means that a reduction in ramping can reduce both the lateral and longitudinal extents of hydropeaking, suggesting that our proposed mitigation measure has the potential to effectively mitigate hydropeaking impacts.

Table 5

Cost–benefit analysis of the MEFI scenario.

Item (€/year)	MEFI, minor increase in emissions	MEFI, no increase in emissions
$d\pi^F$		–269,000
dT		–59,000
<i>WTP</i>	334,247 [83,813–584,682]	466,240 [283,056–648,922]
dW	6,247 [–244,187–256,682]	138,240 [–44,944–320,922]

Our findings indicate that the environmental flow policy can be socially desirable. The willingness to pay for moderate environmental improvement resulting from a stricter flow ramping constraint is proportional to the increase in system balancing costs and the decrease in hydropower revenue. This result applies, when reduced hydropower in the balancing market is compensated by technologies with higher emissions (MEFI scenario). However, when balancing can be achieved without an increase in CO₂ emissions (MEFI, no increase in emissions), the willingness to pay for the improved state of the river increases, widening the gap between local benefits and system costs. Possible balancing resources that may play a larger role in the future power system include wind power, energy storage, and demand side management. For example, as of 2024, wind power is already actively participating in down-balancing offers, while consumption and energy storage technologies contribute to automatic frequency restoration reserves [60]. Thus, any development providing cost-effective, low-emission balancing solutions (e.g., demand response, batteries) leads to more leeway in environmental flow policy design.

However, it is important to consider the following limitations when interpreting the results and planning future research. This study investigated only one environmental flow policy implemented through flow ramping constraints due to the availability of ecosystem service valuation data. We assume that the implementation costs of tighter flow ramping constraints are zero, as this environmental flow policy does not require any direct investment in physical infrastructure. Potential initial or recurring administrative costs should ideally be included in the welfare analysis. However, due to the lack of available data, they are omitted.

Moreover, we focused on one hydropower plant because of data availability (e.g., on flow) and computational complexities in hydropower and hydrological modeling. Future research should analyze different flow ramping parameters and other environmental flow policies for a cascade of hydropower in a river system. In addition, the hydropower optimization model relies on power system data from 2015 to 2019. Since 2019, the share of wind power has significantly increased in the Finnish power system, which may improve the value of hydropower flexibility in the day-ahead and balancing markets.

It is also important to note that further analyses from hydrodynamic modeling outputs, not included in this work, can be developed to determine the hydromorphological and ecological health of the river under current operations and for the proposed mitigation measures. This could also include analysis for sustaining ecological conditions for re-introducing native salmonid fishes to the Kemijoki River. Future studies concerning environmental flow policies should consider the impact of increasing intermittent generation on the value of flexibility as well as how these policies influence hydromorphology and aquatic ecology. Additionally, the impacts of land use changes, such as pumped hydropower investments, and climate change on the effectiveness of environmental flow policies are important topics for future studies. These factors may influence hydropeaking dynamics, river ecology, and the provision of ecosystem services.

Overall, this study shows that tradeoffs exist when implementing environmental flow constraints on hydropower production where some loss of market revenue for power producers can result in significant nonmarket benefits for the river system. This study helps policymakers, environmental regulators, and hydropower companies understand the nuanced impacts of hydropower production and plan policies for sustainable hydropower allocation.

CRedit authorship contribution statement

A. Juutinen: Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Z. Virk:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **H. Huuki:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **E. Ruokamo:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **M. Kopsakangas-Savolainen:** Writing – original draft, Project administration, Funding acquisition, Conceptualization. **A. Torabi Haghighi:** Writing – original draft, Conceptualization. **H. Marttila:** Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors 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. Methods and data in the hydropower multimarket model

In the economic analysis, we study the multimarket operation of a single hydropower plant within the Nordic power markets. In addition to the DAM, we focus on modeling the manual frequency restoration reserve (mFRR) markets, which we will refer to as the balancing market (BM) throughout this article. Importantly, BM prices are used for determining the cost of imbalance power in the imbalance settlement process as a result of the gap between scheduled and realized outcomes [28]. We model the DAM and the BM operation of the hydropower plant under varying environmental flow regulation scenarios. The DAM determines the electricity prices for each hour of day, and it has a large volume turnover [61]. Thus, we model a single hydropower plant as a price taker in the DAM. The electricity system power balance during operation hours is balanced by the Nordic TSOs through the BM [62]. The annual BM

volume is low, approximately 1 % of the consumed electricity [30]. Accordingly, we endogenize the effect of hydropower plant operation to balance market prices.

The hourly DAM and BM generation optimization was conducted based on the actual daily average flow realization in the Ossauskoski power plant for the year 2019 (Figure A1). We exclude two specific periods from the annual optimization horizon, during which we assume that the hydropower plant cannot provide balancing services to the market. First, during the spring inflow period (26.4.- 15.6.2019), the hydropower plant operates at full capacity and must also spill excess water. Second, toward the end of the year (2.11. – 13.12.2019), the hydropower plant must maintain a stable flow to facilitate ice cover formation [63].

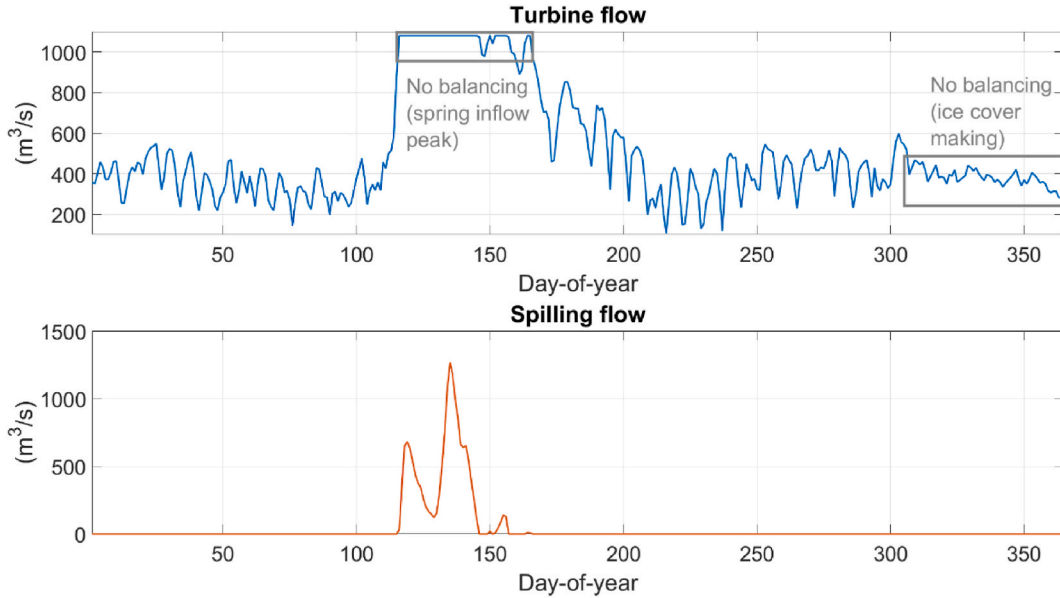


Fig. A1. Ossauskoski hydropower plant average daily turbine flow (top) and average daily spilling flow (bottom) in 2019. The spring inflow peak period and ice cover period are marked with gray boxes.

We optimize hydropower operations in the DAM so that revenue opportunities in the BM are internalized in the bidding strategy. We find the optimal flexibility level b^* used over the annual period so that the expected revenue from both the day-ahead and balancing markets is maximized. In our study case, the flexibility parameter b to be optimized represents the desired flexibility range in flow ramping that the hydropower operator wishes to allocate to the balancing market.

Figure A2 illustrates the impact of the flexibility level b during an upward balancing hour. Assume that the wholesale market price for hour h is higher than the price in the previous hour ($h - 1$). Turbine flow can increase from hour ($h - 1$) to hour h by the maximum amount allowed by the ramping rate constraint θ . If the hydropower operator fully utilizes this ramping potential (as indicated by the dotted line), this leads to an inability to participate in balancing during an upward balancing hour h , resulting in a loss of balancing revenue. Conversely, when the hydropower operator commits to an up-ramping rate of $(\theta - b)$ in the day-ahead market (as indicated by the solid line), the operator can offer an upward balancing flow $b_h \leq b$ (m^3/s) for hour h , resulting in the generation of corresponding balancing energy $q(b_h)$ (MWh). In the latter case, while the hydropower operator forgoes the opportunity to fully capture the revenue potential of the day-ahead market, it gains revenue from the upward balancing in the balancing market.

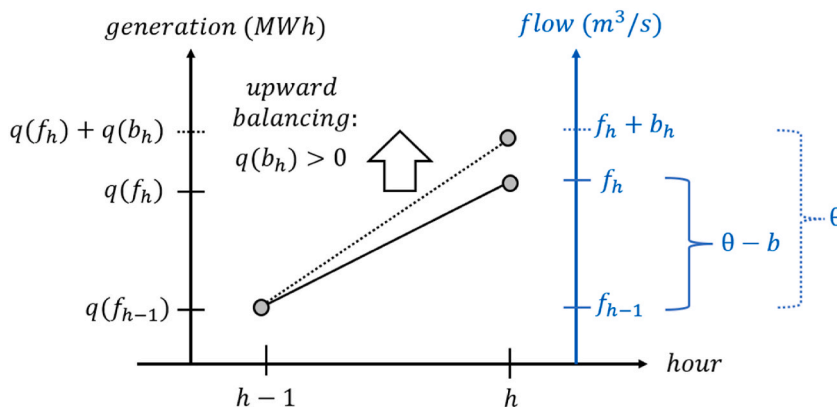


Fig. A2. Illustration of the connection between the balancing flexibility limit b and the potential for balancing services. Example: flow ramping constraint θ and an upward balancing hour.

Appendix A.1. Market data

The day-ahead prices in our model are deterministic. We use hourly prices from 2019 in simulations [64]. According to the price data, the mean value is 44.04 (€/MWh), the standard deviation is 15.29 (€/MWh), the maximum is 200.00 (€/MWh), and the minimum is 0.12 (€/MWh). The balancing market quantities and prices for the years 2015–2019 are used to represent the hydropower balancing operation environment [65]. The ordered balancing quantities over the 2015–2019 period are visualized in Figure A3. During a downward balancing hour, the average ordered balancing energy was 61.7 (MWh). During an upward balancing hour, the average ordered balancing energy was 59.0 (MWh). There is considerable variation in the required balancing energy, with the 95th percentile for downward balancing energy being 182.0 (MWh) and 175.0 (MWh) for upward balancing energy.

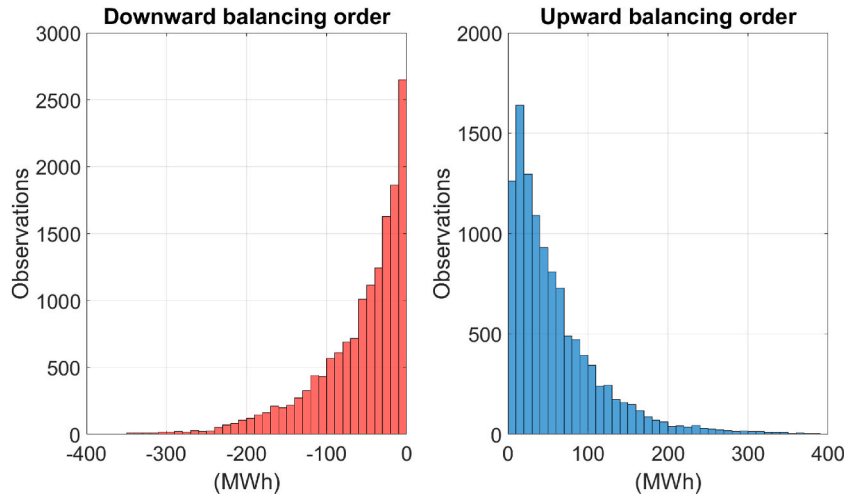


Fig. A3. Ordered downward (left) and upward (right) energy during 2015–2019. (Source: [66]).

The upward balancing price is the highest accepted bid for upward energy. This price is at least the day-ahead wholesale price in the Finnish price area on Nord Pool. The downward balancing price is the lowest accepted bid for downward energy. This price never exceeds the day-ahead wholesale price in the Finnish price area. Figure A4 illustrates the percent price premium for upward and downward balancing, represented as the balancing price divided by the wholesale electricity price, $\rho = (p^{BM} / p^{DAM}) \cdot 100$, during a balancing hour.

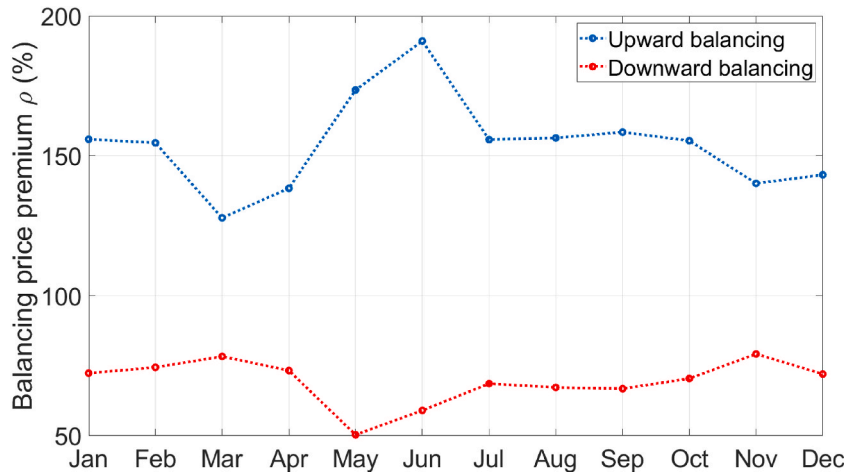


Fig. A4. Average monthly price premium for downward- and upward-balancing energy during 2015–2019 (calculated from data in Ref. [66]).

An interesting feature of the balancing energy market is the tendency for the balancing direction to remain in the current state. Table A1 shows the transition probability matrix for the balancing directions during the 2015–2019 period. The matrix demonstrates a form of balancing direction stability, with a substantial portion of the probability mass concentrated on the diagonal. Additionally, since the need for balance is not independent for each hour, it should be noted that the linearity of expectations property, as described in Equation (4) in the main text, does not hold in the context of the hydropower revenue maximization condition. Expectations need to be calculated over the entire modeling period.

Table A1
Transition probability matrix for balancing market states.

	Downward balancing	No balancing	Upward balancing
Downward balancing	0.782	0.167	0.051
No balancing	0.149	0.719	0.132
Upward balancing	0.059	0.219	0.722

For the hydropower simulation, we need to make an assumption about the simulated hydropower balancing services in the business-as-usual (BAU) scenario. To do this, we rely on information concerning the role of hydropower in the balancing market. We use the average monthly shares of hydropower, denoted as τ^{month} , in order of upward and downward balancing in Finland (Figure A5). Subsequently, we assumed that the Ossauskoski hydropower plant represents 4.2 % of the total hydropower balance. This assumption is based on the statistic that the average annual generation of the Ossauskoski plant is 501 GWh, while the average annual generation of hydropower plants exceeding 10 MW is 12,012 GWh [67]. We assume that the balancing shares are equivalent to the generation shares, and we establish their relation as follows: $\omega = \frac{501 (GWh)}{12012 (GWh)} = 0.042$. Given the required balancing energy $q_{h,d,y}^{BM}$, we can calculate the benchmark Ossauskoski balancing energy for each of the hours of day $h \in \{1, \dots, H = 24\}$, days of year $d \in \{1, \dots, D = 365\}$, and balancing market realization year $y \in \{1, \dots, Y = 5\}$, offered by the Ossauskoski power plant as

$$\bar{b}_{h,d,y} = q_{h,d,y}^{BM} \tau^{month} \omega, \text{ for } month \in M(d), \tag{A1}$$

where operator M maps the day-of-year index d to the month-of-year index $month \in \{1, \dots, 12\}$.

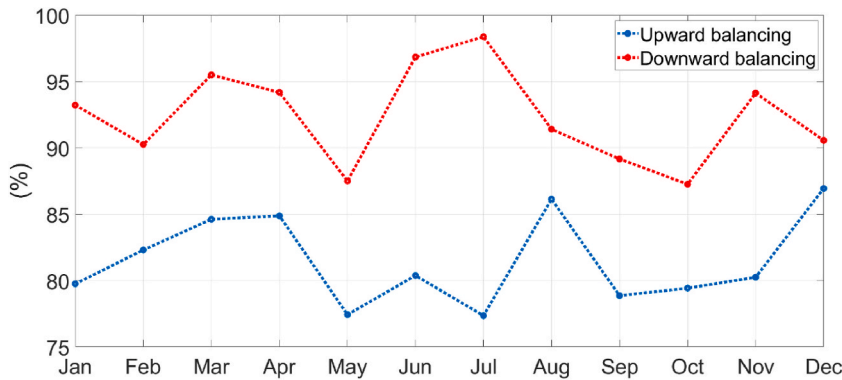


Fig. A5. Average monthly percentage share of hydropower plants in order of downward and upward balancing during 2018–2019 (Source: [65]).

We conduct a linear regression analysis to model the relationship between the balancing price premium and the ordered balancing power. Figure A6 shows the marginal effect of an increase in the order balancing (MWh) quantity on the balancing price premium (%). For downward balancing hours, on average, an increase in the order balancing quantity (MWh downwards) has a negative effect of -0.13 percentage points on the balancing price premium. The impact of downward balancing demand is stronger in May, with the effect of balancing quantity on the balancing price premium being -0.609 %. For upward balancing, an increase in the ordered balancing quantity (MWh upwards) results, on average, in 1.15 percentage point increase in the upward balancing premium. In May and June, this effect was more substantial, reaching 2.51 % and 3.01 %, respectively. This pattern underscores the relative scarcity of balancing market supply during the high hydropower inflow period in spring. During this period, hydropower plants exhibit decreased flexibility in responding to the electricity system’s balancing requirements due to the flow of water through turbines or spillage.

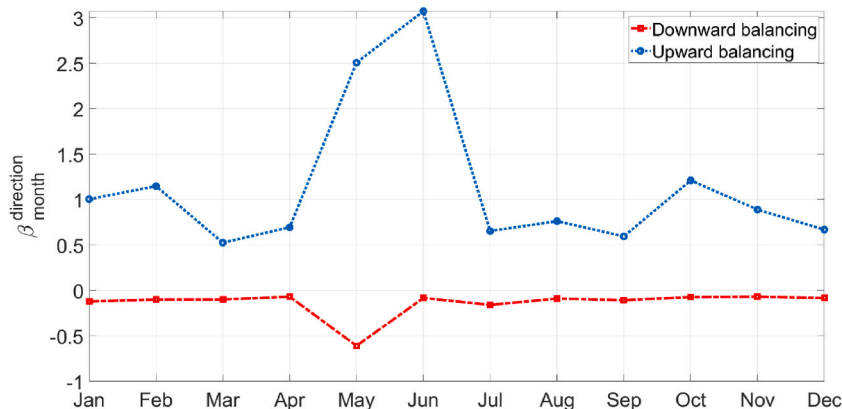


Fig. A6. The marginal effect of an additional ordered balancing quantity on the balancing price premium.

The realized balancing price $p_{h,d,y}^{BL}$ for hour-of-day h , day-of-year d and balancing market realization y is a function of the required balancing market quantity $q_{h,d,y}^{BM}$, the balancing price premium $\rho_{h,d,y}$ and the offered balancing quantity of the hydropower plant $b_{h,d,y}$:

$$p_{h,d,y}^{BM}(b_{h,d,y}|q_{h,d,y}^{BM}, \rho_{h,d,y}) = \begin{cases} p_{h,d}^{DAM} \{ \rho_{h,d,y} \beta_{month}^{upward} (b_{h,d,y} - \bar{b}_{h,d,y}) 10^{-2} \}, \text{ for } q_{h,d,y}^{BM} > 0, \text{ month} \in M(d) \\ p_{h,d}^{DAM}, \text{ for } q_{h,d,y}^{BM} = 0 \\ p_{h,d}^{DAM} \{ \rho_{h,d,y} \beta_{month}^{downward} (b_{h,d,y} - \bar{b}_{h,d,y}) 10^{-2} \}, \text{ for } q_{h,d,y}^{BM} < 0, \text{ month} \in M(d) \end{cases}, \quad (A2)$$

where operator M maps the day-of-year index d to the month-of-year index $month \in \{1, \dots, 12\}$.

Appendix A.2. Hydropower optimization model

Optimization of the flow of the Ossauskoski hydropower plant was performed as follows. We find the optimal turbine flow for each hour-of-day, $h \in \{1, \dots, H = 24\}$, $f^d = [f_1^d, \dots, f_H^d]$ for each day-of-year $d \in \{1, \dots, D = 365\}$, given the exogenous flow ramping constraint θ , set by the regulator, and balancing flexibility level b , set by the hydropower plant for the total optimization period:

$$\max_{f^d} \pi_d^{DAM}(f^d) = \sum_{h=1}^H p_{h,d}^{DAM} q(f_h^d), \forall d = \{1, \dots, D = 365\}, \quad (A3)$$

where π_d^{DAM} is the day-ahead market revenue (€), $p_{h,d}^{DAM}$ is the day-ahead market price (€/MWh), and $q(f_h^d)$ is the hourly electricity generation (MWh) given average flow f_h^d (m^3/s) during hour h . The conversion rate from flow f to generation q is set as

$$q = \begin{cases} 0.1209f, \text{ if } f \in [100, 900] \text{ (} m^3/s \text{)} \\ 0.1148f, \text{ if } f \in]900, 1080] \text{ (} m^3/s \text{)} \end{cases}, \quad (A4)$$

where this hydropower generation conversion is based on discussions with personnel in Kemijoki Oy.

The revenue maximization for each day-of-year $d \in \{1, \dots, D = 365\}$ in Equation (A3) is subject to the following constraints:

$$\sum_{h=1}^H f_h^d = F^d, \quad (A5)$$

$$\underline{f}^{DAM} \leq f_h^d \leq \bar{f}^{DAM}, \text{ for } h = \{1, \dots, H\}, \quad (A6)$$

$$-(\theta + b) \leq f_1^d - f_H^{d-1} \leq (\theta + b), \text{ for } h = 1, \quad (A7)$$

$$-(\theta + b) \leq f_h - f_{h-1} \leq (\theta + b), \text{ for } \{h = 2, \dots, H\}, \quad (A8)$$

where constraint (A5) describes the total flow constraint. The total flow for days of year d , F^d , is based on the observed daily flow data shown in Figure A1. Constraint (A6) describes the turbine flow range used in day-ahead scheduling. Constraint \underline{f}^{DAM} is the minimum flow used in day-ahead turbine flow optimization. We assumed that the minimum flow used in the Ossauskoski hydropower plant was 100 (m^3/s). We leave a 5 (m^3/s) balancing margin for the minimum load in the day-ahead scheduling; thus, \underline{f}^{DAM} is set to 105 (m^3/s).

Constraint \bar{f}^{DAM} is the maximum flow used in day-ahead turbine flow optimization. We assume that the hydropower plant utilizes a high-efficiency flow range of up to 900 (m^3/s) in day-ahead market scheduling and leaves the turbine flow potential up to 900 (m^3/s) available for balancing if needed. Consequently, \bar{f}^{DAM} is set to 900 (m^3/s). Constraints (A7) and (A8) describe the flow ramping conditions described by the combination of the environmental flow ramp rate θ and the balancing flexibility level b .

The day-ahead turbine flow schedule affects the hydropower producer's ability to offer balancing energy. For up-balancing hour $q_{h,d,y}^{BM} > 0$,

$$b_{h,d,y} = \min\{\bar{b}_h, \bar{f} - f_h, \theta - \max\{0, (f_h - (f_{h-1} + b_{h-1}))\}\}, \theta - \max\{0, (f_h - f_{h+1})\}, \}, \quad (A9)$$

where $\bar{b}_h = \min\{\mu\bar{r}, \varphi^{upward}\bar{b}_{h,d,y}\}$, $\mu = 0.25$, $\bar{r} = 250$ (m^3/s), $\varphi^{upward} = 1.2$, and $\bar{b}_{h,d,y}$ is the benchmark hydropower plant balancing offerings for hour-of-day h , day-of-year d and balancing year y . The constraint $\mu\bar{r}$ implies that the hydropower plant can offer a

maximum of 25 % of its nominal ramping capacity to the balancing market [68]. In this case, the maximal ramping \bar{r} is 250 (m^3/s), i.e., the ramping constraint of the BAU scenario. Constraint $\varphi^{upward} \bar{b}_{h,d,y}$ sets an upper bound for the simulated hydropower plant's upward balancing offer compared to the balancing offer estimated in the benchmark case. For upward balancing, the φ^{upward} constraint value of 1.2 provided a good match between the simulated hydropower plant in the BAU scenario and the benchmark estimate.¹ The rest of the flow constraints in Equation (A9) describe the constraint that upward balancing is constrained by the maximum turbine flow $\bar{f} = 1080$ (m^3/s) and that flow ramping cannot exceed the ramping constraints set by parameters θ and b .

For down-balancing hour $B_t < 0$,

$$b_{h,d,y} = \max\left\{ \underline{b}_h; \underline{f} - f_h, -\theta - \min\{0, (f_h - (f_{h-1} + b_{h-1}))\}, -\theta - \min\{0, (f_h - f_{h+1})\} \right\}, \tag{A10}$$

where $\underline{b}_h = \max(\mu \underline{r}, \varphi^{downward} \bar{b}_{h,d,i})$, $\mu = 0.25$, $\underline{r} = -250$ (m^3/s), $\varphi^{upward} = 2.4$, and $\bar{b}_{h,d,y}$ is the benchmark hydropower plant balancing offerings for hour-of-day h , day-of-year d and balancing year i . The constraint $\mu \underline{r}$ implies that the hydropower plant can offer a maximum of 25 % of the nominal ramping capacity of the hydropower plant to the balancing market. In this case, the minimum downward ramping \underline{r} is -250 (m^3/s), i.e., the ramping constraint of the business-as-usual scenario. Constraint $\varphi^{downward} \bar{b}_{h,d,y}$ sets a lower bound for the simulated hydropower plant downward balancing offer than for the balancing offer estimated in the benchmark case. For downward balancing, the φ^{upward} constraint value 2.4 provided a good match between the simulated hydropower plant in the BAU scenario and the benchmark estimate.² The rest of the flow constraints in Equation (A10) describe the constraint that downward balancing is constrained by the minimum turbine flow $\underline{f} = 100$ (m^3/s) and that flow ramping cannot exceed the ramping constraints set by parameters θ and b .

Given that the day-ahead turbine flow ramp, $f_h - f_{(h-1)}$, is a function of the balancing flexibility variable b , we can write the balancing quantity of the hydropower plant as a function of variable b and environmental policy constraint θ : $b_t(b, \theta)$. The expected profit from the balancing market can be written as

$$E\left\{ \sum_d^D \pi_d^{BM}(b, \theta) \right\} = \sum_{d=1}^D \sum_{h=1}^H \sum_{y=1}^Y \nu_y P_{h,d,y}^{BL} \left(b_{h,d,y} \mid q_{h,d,y}^{BM}, \rho_{h,d,y} \right) q(b_{h,d,y}(b, \theta)), \tag{A11}$$

where ν_y is the probability of balancing market realization $y \in \{1, \dots, Y\}$.

According to Equation (1) in the main text, the hydropower operator chooses balancing flexibility b so that the total revenue is maximized:

$$\pi = \max_b E\left\{ \sum_{d=1}^D [\pi_d^{DAM}(f_d^*(b, \theta)) + \pi_d^{BM}(b, \theta)] \right\}, \tag{A12}$$

given the environmental policy constraint θ , where $f_d^* \in \mathbb{R}^H$ is the optimal day-ahead turbine flow allocation for each hour-of-day $h \in \{1, \dots, H = 24\}$ for each day-of-year $d \in \{1, \dots, D = 365\}$.

APPENDIX B. Additional results

Table B1

The effect of the balancing flexibility parameter (b) on DAM and BM revenue in the business-as-usual (BAU) and moderate environmental flow improvement (MEFI) scenarios.

		Revenue (M€)	Balancing flexibility parameter b (m^3/s)					
			0	5	10	15	20	25
BAU	DAM	24.019	24.014	24.009	24.005	24.002	23.999	23.993
	BM	0.045	0.056	0.066	0.074	0.080	0.084	0.088
	Total	24.064	24.070	24.075	24.079	24.082	24.083*	24.081
MEFI	DAM	23.798	23.783	23.760	23.743	23.719	23.696	23.671
	BM	0.013	0.031	0.047	0.058	0.065	0.070	0.073
	Total	23.811	23.814*	23.807	23.801	23.784	23.766	23.744

¹ The average annual sum of hydropower benchmark upward-balancing energy, $\frac{1}{Y} \sum_{y=1}^Y \sum_{d=1}^D \sum_{h=1}^H \bar{b}_{h,d,y}$, is 3.107 (GWh/a). The average annual sum of simulated hydropower upward-balancing energy in the BAU scenario, $\frac{1}{Y} \sum_{y=1}^Y \sum_{d=1}^D \sum_{h=1}^H b_{h,d,y}$, is 3.121 (GWh/a).

² The average annual sum of hydropower benchmark downward-balancing energy, $\frac{1}{Y} \sum_{y=1}^Y \sum_{d=1}^D \sum_{h=1}^H \bar{b}_{h,d,y}$, is -4.982 (GWh/a). The average annual sum of simulated hydropower downward-balancing energy in the BAU scenario, $\frac{1}{Y} \sum_{y=1}^Y \sum_{d=1}^D \sum_{h=1}^H b_{h,d,y}$, is -5.434 (GWh/a).

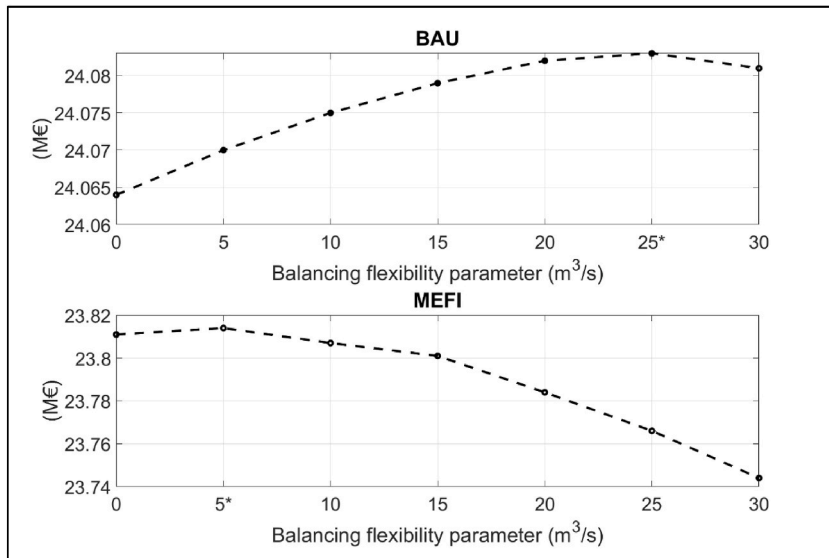


Fig. B1. Total revenue as a function of the balancing flexibility parameter (b) in business-as-usual (BAU) and moderate environmental flow improvement (MEFI) scenarios. The total revenue function is concave in the optimal balancing flexibility region (market by *).

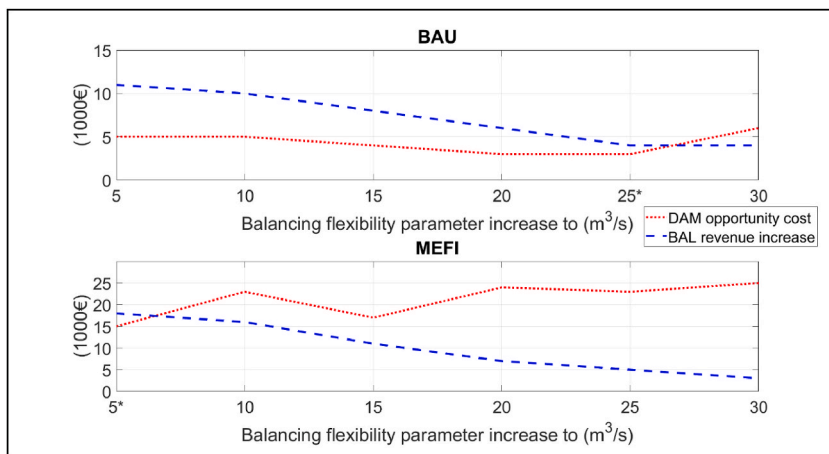


Fig. B2. The marginal effect of an increase in the balancing flexibility parameter (b) on DAM and BM revenue in the business-as-usual (BAU) and moderate environmental flow improvement (MEFI) scenarios.

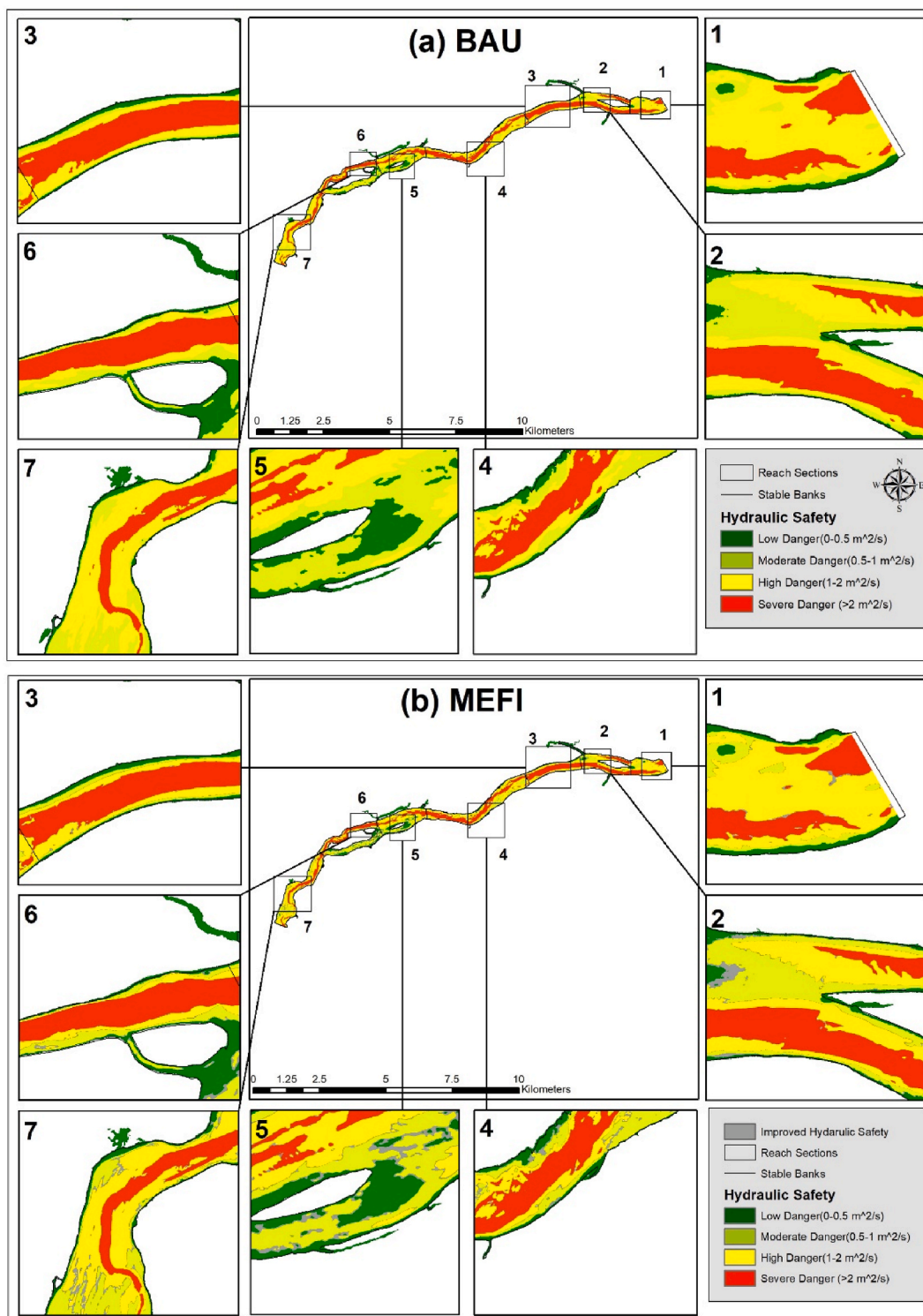


Fig. B3. (a) Hydraulic safety as per Birchof's thresholds in the business-as-usual scenario (BAU). (b) Hydraulic safety under moderate environmental flow improvement (MEFI) with a 50 % reduction in ramping. The gray area in Panel (b) represents the improvement in hydraulic safety to the next category i.e., from "High" to "Moderate" and "Moderate" to "Low Danger", because of a reduction in ramping.

Figure B3 shows the hydraulic safety in the reach defined as the product of depth and velocity (HV) compared to the safety thresholds developed by Ref. [52]. The green areas on the map represent areas at minimal risk, and the red areas represent areas at higher risk for in-stream recreation. As a result of improvements in environmental flow and a 50 % reduction in ramping, the hydraulic

safety in the reach improved slightly, as shown in Figure B2(b). A total of 3.4 % (46327 m²) of the area of the channel was converted to “low” risk, and 0.1 % (2292 m²), 1.2 % (29602 m²) and 1.1 % (25327 m²) reductions were observed in the “moderate”, “high”, and “severe” risk areas, respectively. Although the reduction of high-risk areas to low-risk areas slightly improved, this change was not significant considering the size of the reach.

Data availability

Data will be made available on request.

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