Valued peaks: sustainable water allocation for small hydropower plants in an era of explicit ecological needs

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Abstract

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Abstract

Optimising hydropower operations to balance economic profitability and support functioning ecosystem services is integral to river management policy. In this article, we propose a multi-objective optimization framework for small hydropower plants (SHPs) to evaluate trade-offs among environmental flow scenarios. Specifically, we examine the balance between short-term losses in hydropower generation and the potential for compensatory benefits in the form of revenue from recreational ecosystem services, irrespective of the direct beneficiary. Our framework integrates a fish habitat model, a hydropower optimization model, and a recreational ecosystem service model to evaluate each environmental flow scenario. The optimisation process gives three outflow release scenarios, informed by previous streamflow realisations (dam inflow), and designed environmental flow constraints. The framework is applied and tested for the river Kuusinkijoki in North-eastern Finland, which is a habitat for migratory brown trout and grayling populations. We show that the revenue loss due to the environmental flow constraints arises through a reduction in revenue per generated energy unit and through a reduction in turbine efficiency. Additionally, the simulation results reveal that all the designed environmental flow constraints cannot be met simultaneously. Under the environmental flow scenario with both minimum flow and flow ramping rate constraints, the annual hydropower revenue decreases by 16.5%. An annual increase of 8% in recreational fishing visits offsets the revenue loss. The developed framework provides knowledge of the costs and benefits of hydropower environmental flow constraints and guides the prioritizing process of environmental measures.

Introduction

Hydropower is the primary renewable electricity source worldwide (Zarfl et al., 2015) and thus has a crucial role to play in accelerating the share of renewables in global energy systems. However, hydropower production has environmental and social costs, which in some cases can outweigh its benefits. Hydropower operations compromise specific ecosystem services (ES) provision and are among the key drivers responsible for unprecedented rates of declining freshwater biodiversity (Dudgeon et al., 2006). Therefore, to balance ecological conservation, social impacts, and economic development, there is a need for a much broader adaptation of hydropower operational regimes that consider all these aspects (Couto et al., 2021; Sabo et al., 2017; Winemiller et al., 2016). Such adaptations have been initiated in various contexts to optimize hydropower production while prioritizing ecological needs (Halleraker et al., 2007; Horne et al., 2017; Kuriqi et al., 2019; Willis et al., 2022) .

Building high numbers of large hydropower plants (LHPs) in developed countries has attracted substantial scientific activity and international scrutiny (Wagner et al., 2015). This has given rise to the growing negative sentiment surrounding large dams (Ellis & Jones, 2013), whereas the environmental impacts of small hydropower plants (SHPs) have been largely ignored (Couto et al., 2021; Jager et al., 2015). Perhaps this oversight, along with the economic incentives offered for sustainable energy development, particularly in China and Europe, have contributed to the initial growth of SHPs (Paish, 2002; Tang et al., 2012). SHPs are often defined as plants with a capacity of less than 10 MW, but this threshold may differ between countries (T. B. Couto & Olden, 2018). Now SHPs are a critical component of future renewable energy strategies due to the belief that SHPs have a lower socioecological impact (Gleick, 2009; Kao et al., 2014). However, scientific evidence suggests that compared to LHPs the ecological impact of SHPs per megawatt of power produced may be disproportionally higher (Kibler & Tullos, 2013; Ramos et al., 2023; Timpe & Kaplan, 2017; Ziv et al., 2012). SHPs have also been documented as the cause of significant impact and damage at ecosystem and social levels (Fearnside, 2016; Tahseen & Karney, 2017).

Today, at least 82,891 SHPs (11 times the number of LHPs) are either in operation or under construction in 150 countries (T. B. Couto & Olden, 2018). This number could triple, with an additional 181,976 plants that could be installed if all potential capacity were to be developed (T. B. Couto & Olden, 2018). This projected rise in SHPs can have detrimental impacts on river habitat quality and affect the persistence of migratory fish and cultural ES they support (Winemiller et al., 2016). Migratory fish have key roles in food webs and ecosystem functioning (Costa-Pereira et al., 2018; Flecker et al., 2010), hence their wellbeing can be a good gauge of how well the ecosystem is functioning. Fish habitat quality depends on hydro-morphological and ecological dynamics (Vermaat et al., 2013), which are fundamentally tied to water availability's spatial and temporal variability, i.e., to the flow regime (Zimmerman et al., 2010). The impact of SHPs on natural river flow regimes is influenced by various operational factors, such as whether the SHP is a peaking or run-of-river plant, its size, and the presence of a reservoir. While not solely dictated by market price variability, it can still be a contributing factor. As a result of these practices, hydropeaking occurs, which refers to releasing sudden flows during peak energy demand periods. Global power markets have undergone deregulation and price liberalization (Loi & Jindal, 2019; Pepermans, 2019), with the aim of allowing them to be more competitive and efficient (Halkos, 2019; Marino et al., 2019). As the operational regimes of SHP connected to a deregulated market mimics the price variation in it, sub-daily flow regimes of such river also become unpredictable.

The effects of hydropeaking on river ES are still under investigation (Carolli et al., 2017). Despite gaining attention in the recent times there are only old and limited studies done to quantify cultural river ES, such as recreational possibilities, concerning flow regime alteration (Russi, 2013; Shelby et al., 1998). These studies have primarily focussed on the economic value of selected ES (Fanaian et al., 2015), an approach evaluating river ES mainly based on geographical and morphological features (Large & Gilvear, 2015) and water abstraction associated with hydropower production (Carolli et al., 2017). However, little work has been done to develop quantitative, predictive tools to evaluate the impact of hydropeaking on river recreational ecosystem services (RES).

Various forecasting methods have been employed to improve both dam design and operations at multiple time scales for flood control and irrigation purposes (Anghileri et al., 2016a; Bertoni et al., 2021; Raso et al., 2014). These studies evaluate either the sensitivity of forecast value to discrete dam features (such as dam size, storage capacity-inflow ratios, and storage capacity-demand ratios) or, as Bertoni, Giuliani et al. (2021), integrating planning and operating policies based on streamflow forecasts. For hydropower facilities, the operation problem requires sequential decision-making optimization methods such as dynamic programming (Feng et al., 2017) or reinforcement learning (Xu et al., 2020). In addition, environmental, technical, and regulatory constraints affect hydropower plant operation (Stoll et al., 2017). Comparing the benefits of environmental flow policies with the economic costs to hydropower generation requires an understanding of both the river ecosystem and the electricity markets (Bejarano et al., 2019; Widén et al., 2022).

Here we propose a multi-objective optimization framework for water resource allocation to ensure sustainable operation of SHPs. We analyse the impact of river flow to habitat conditions and incorporate the analysed flow restrictions into the hydropower optimization algorithm. We employ a Q-learning algorithm (see Sutton & Barto, 2018) to train the optimal turbine flow release policy under various inflow conditions from the years 2000-2017. The resulting optimal policy is then applied to the inflow conditions for the operation year 2018. With this SHP optimisation approach, we can quantify the effect of environmental flow constraints in terms of the gains in the suitable habitat area and the loss in hydropower revenue.

Given this background, the main aim of this work is to create a SHP operation optimization framework that takes into consideration environmental, social, and economic feedback. To achieve this, we i) apply a dynamic optimisation sub-daily water allocation model that consider various environmental flow constraints and varying electricity prices and, ii) determine the monetary impact on river ecosystem services of a recreationally relevant subarctic river. The developed framework provides knowledge with regards to the environmental adaptation of hydropower and prioritizing environmental measures. The framework was applied and tested at a SHP called the Myllykoski hydropower plant (1 MW) on the river Kuusinkijoki, in north-eastern Finland. It is a habitat for locally important migratory brown trout and grayling fish populations.

Study area and its relevance

The study was conducted in the river Kuusinkijoki (Fig. 1), located in north-east Finland's Ruka-Kuusamo area. Tourism has a significant role in the area as one of the largest ski resorts in Finland, Ruka, is located there. Another important tourist attraction in the area is the Oulanka national park. Around 1 million tourists visit Ruka-Kuusamo annually, leaving behind a total revenue of over 90 million euros and providing full-time employment to over 800 people. One of the key tourism activities is recreational fishing. The River Kuusinkijoki is a favourite destination for recreational anglers for grayling and trout fishing. Two other attractive rivers for recreational fishing in the area are the River Kitkajoki and the River Oulankajoki, which both belong to the same river system together with the River Kuusinkinjoki.

The River Kuusinkijoki has a yearly average flow of 9 $m^3 s^{-1}$, a peak flow of 60 $m^3 s^{-1}$ and a catchment area of 1,020 km^2, with snowmelt serving as the major source for floods. The area receives an annual precipitation of 554 mm and has an average air temperature of 9 °C. The catchment area is composed of various landscape elements mainly from boreal forests, lakes and peatlands. The Kuusinkijoki is regulated for hydropower by the Myllykoski power plant, which has been in operation since 1957. The Myllykoski plant is a SHP with 6 GWh average annual energy production and a 1.4 MW nominal power. We chose the flowing river Oulankajoki as a free-flowing counterpart to evaluate the deviation of the Kuusinkijoki from natural flow dynamics. A river stretch was selected that encompasses various existing habitat and morphologic conditions to allow detailed investigation of their characteristics (bathymetry and hydraulics). The choice of the investigation's reach was made based on the importance of the stretch for our target fish species (grayling and migrating brown trout).

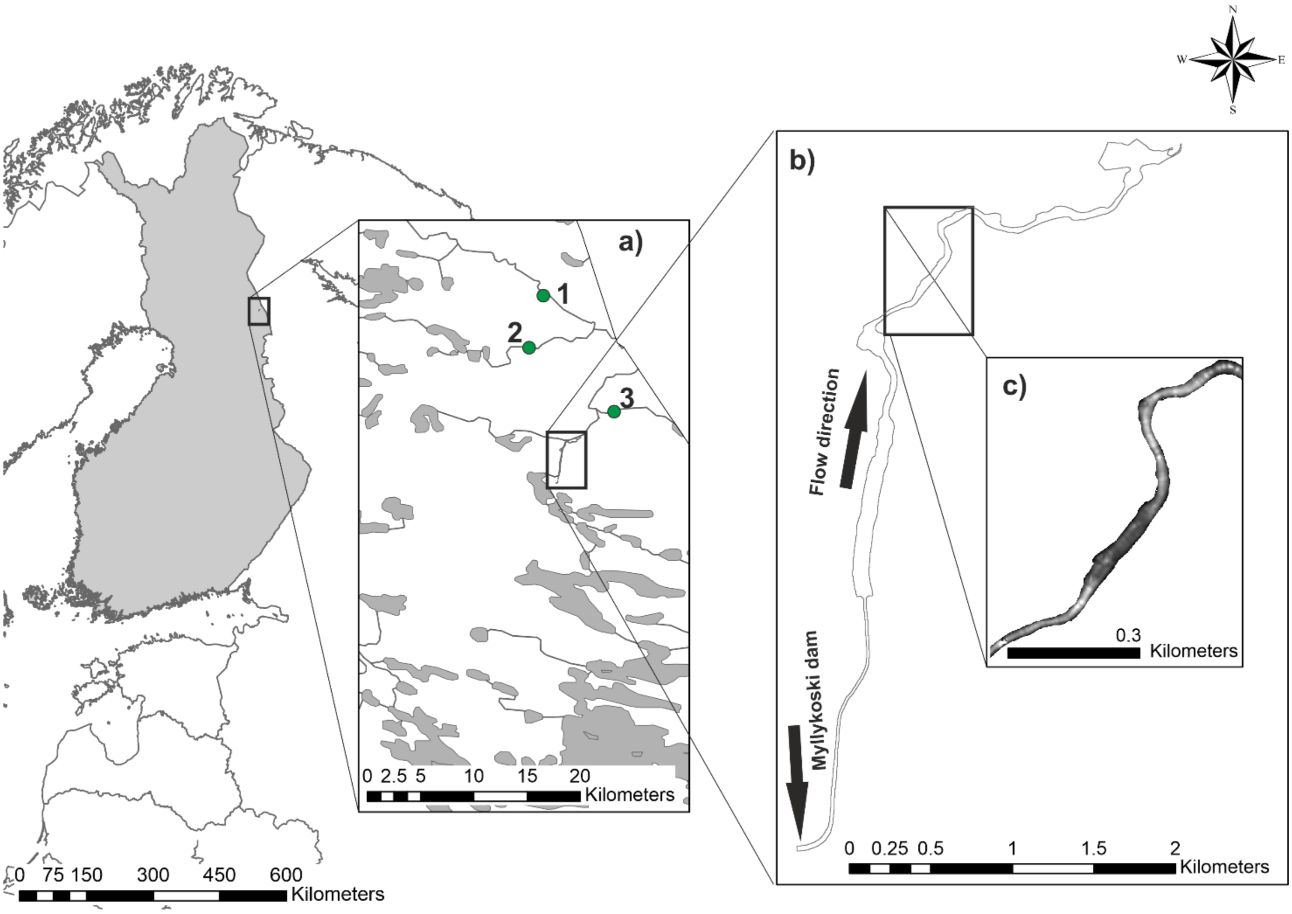

Figure 1. Location of the studied river section. In panel a, points 1, 2 and 3 are on the Oulankajoki, Kitkajoki and Kuusinkijoki respectively. The arrowhead at the bottom left corner of the panel shows the location of the Myllykoski dam. The whole modelled reach is shown in panel b, with highlighted area of interest in panel c.

Materials

River bathymetry, hydrological data and calculation of hydraulic variables

We used previously collected river bathymetry, fish preference and morphology data, covering around 6 km of the river section downstream from the Myllykoski hydropower (for more details see Kylmänen et al., 2001; Nykänen et al., 2004). The bathymetry points were first combined into a point cloud used as the empirical IDF interpolation method using the average method for overlapping points in ArcGIS (ESRI Inc., 2020). The whole reach of the Kuusinkijoki river, from the Myllykoski dam downstream to the Melalampi lake, was modelled in a 1m-by-1m Digital Elevation Model (DEM) of bathymetry. Bathymetric data was obtained through previous field campaigns, and the results have been previously published (Lahti, 2009), the average and largest differences between the model and actual measurements were 4.5 cm and 14 cm, respectively. Hourly river flow data which is the temporal resolution our whole study is based on, was obtained by placing a request with the Finnish research institute (SYKE).

Hourly electricity wholesale prices

In the economic model, year 2018 hourly electricity prices for Finland are used as inputs and modelled as deterministic. The average price in 2018 was 46.8 ($€/MWh$), and the standard deviation of prices was 15.1

$(€/MWh)$. The minimum price of 1.6 $(€/MWh)$ occurred on the 9th of May at 1 am, and the maximum price of 255.0 $(€/MWh)$ occurred on the 3rd of January at 9 am.

Methods

River flow hydraulic model

A two-dimensional hydraulic model was set up in HEC-RAS 5.0.7 for the simulation. HEC-RAS, which stands for Hydrologic Engineering Center's River Analysis System, is a software developed by the U.S. Army Corps of Engineers for simulating the hydraulic characteristics of water flow in river channels and around structures (US Army Corps of Engineers Hydrologic Engineering Center, 2016). In our study, a terrain file of 1 × 1 m resolution and a computational mesh size of 4 × 4 m was used in the model setup. The underlying 1 × 1 m terrain was still the computational basis for all depth and velocity simulations. Additional finer cells and break lines were included in areas where a higher resolution was needed (along riverbanks, islands, and side channels). The friction slope at the downstream section of the reach was approximated to be the normal depth (0.001), calculated using the bathymetry topography and set as the lower boundary condition. We calibrated the model using the Manning's n coefficient with observed depths at specific discharges. For the riverbed roughness, Manning's coefficients ranged from n = 0.015 (channel with small lakes) to n = 0.09 (channel with bushes, small islands, and higher resistance) (Chow, 1959). To validate the simulation results, observed data collected from fixed locations (supplementary figure S2) at discharges of 3.2 m^3s^{-1}, 3.8 m^3s^{-1} and 17 m^3s^{-1} was compared with simulated depth values. The coefficients of determination (R^2) for the correlation between simulated and observed water depth values in river sections were > 0.95 for all three observed velocities at 60 different locations (Fig. 2, a).

River flow hydraulics (depth and velocity) were simulated for 2, 3, 4, 5, 6, 8, 10, 12, 14, 17, 20, 25, 28, and 35 m^3s^{-1} of dam outflow for the entire reach (Fig. 4, b), giving varying magnitudes and patterns of flow depth and velocity downstream. The resulting distributions of hydraulic variables were exported in 1 × 1 m cells for the river section and river reach occurring flow. This simulated river flow hydraulics served as an input for the fish habitat model to quantify the fish habitat area affected under varying Q values. Even though the whole river channel below the Myllykoski dam was modelled (Fig 1, b), we focussed on the channel section in fig 1 c) because that section is identified as the most critical habitat for the target species for recreational fishing. Main terrain modification and river flow hydraulic modelling steps are summarised in figure 2.

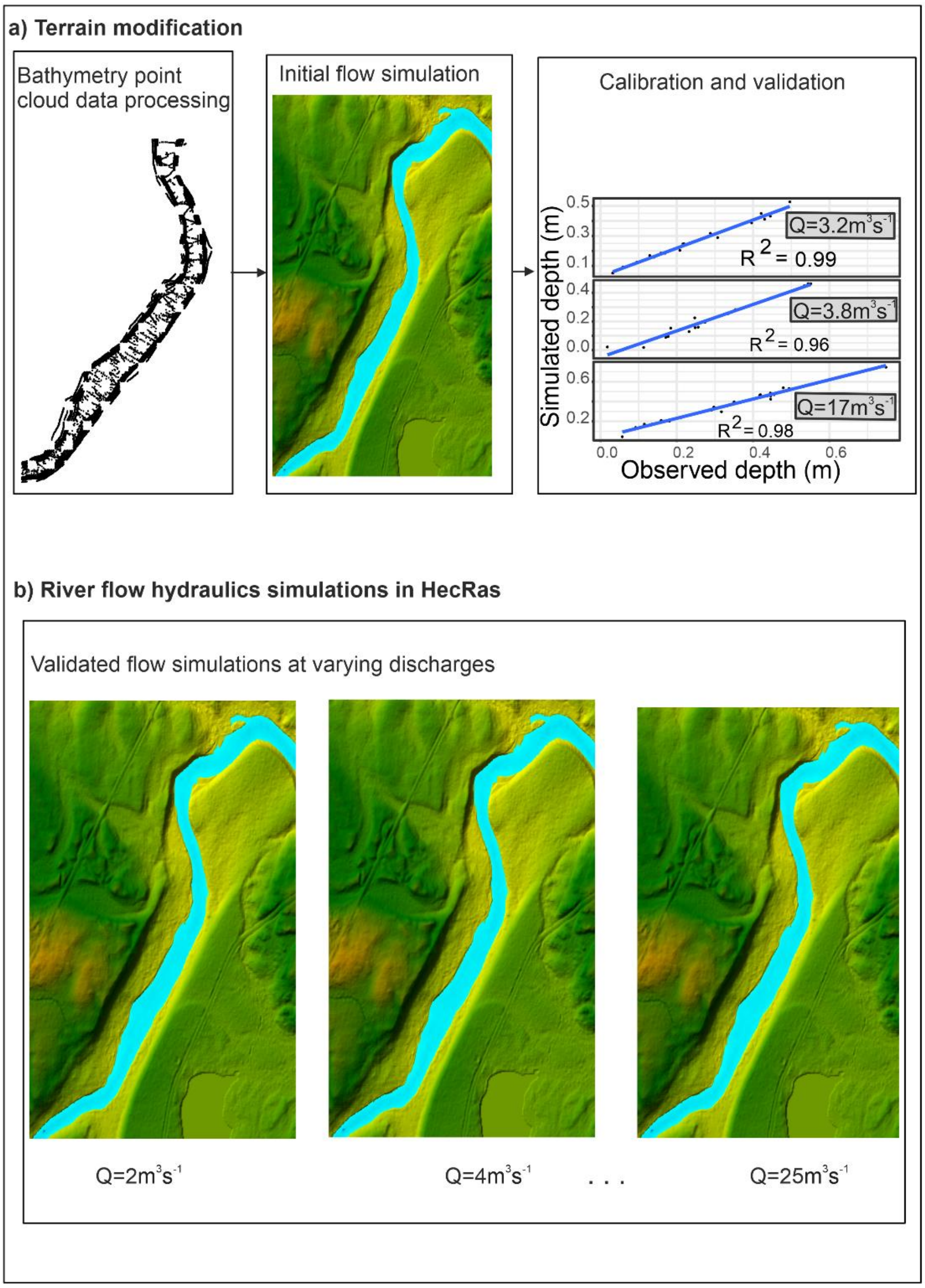

Figure 2. Summarised steps taken during terrain modification, a, and river flow hydraulic modelling, b.

Fish habitat model

Habitat Suitability (HS) simulations are used for assessing the preferred environmental conditions for various fish species under different flow conditions. The primary aim of these simulations is to ensure the long-term viability and sustainability of aquatic habitats. We conducted HS simulations and the quantification of suitable fish habitats using the fish habitat module from the CASiMiR numerical modeling toolbox. CASiMiR, which stands for Computer-Aided System for Modelling in Rivers, is a flexible numerical modeling toolbox developed to simulate and assess fish habitats in flowing waters under varying hydraulic conditions (Schneider et al., 2001). This toolbox was developed and applied in the early 1990s and has been used in numerous studies (Mouton et al., 2007). In the presented research, fish habitats were modelled based on 1 × 1 m resolution data, resulting in a detailed HS simulation of a relatively short river stretch (1.2 km).

The values assigned to the two input variables, depth, and flow velocity, were defined by the preference curves for brown trout and grayling juveniles and their spawning areas. Due to the lack of data for the dominant substrate, it was not included in the analysis. First, the fish module imports the flow velocities and water depths for the reach from the HecRAS model. After importing the biological data in preference curves, each flow rate's habitat suitability (HS) is computed using hydraulic characteristics. Preferential curve data for the target species is shown in supplementary table S1.

Four criteria were used to assess the change in HS. The weighted usable area (WUA) was obtained by integrating habitat quality over the entire studied stretch (Eq. (1)).

$$WUA = \sum_{i=1}^{n} A_i \, HSI_i = f(Q)[m^2] \quad (1)$$

WUA is expressed as an area (m^2), and its theoretical maximum value is the total wetted area of a reach that could be obtained if all cells had some level of habitat suitability. A_i is area of the i^{th} cell, HSI_i is the Habitat Suitability Index of cell i and Q is the flow rate expressed in $m^3 s^{-1}$.

The Hydraulic Suitability Index (HSI), defined between 0 and 1, is calculated by taking a geometric mean of preferential values of depth and velocity in a defined area Eq. (2).

$$HSI_i = \sqrt{PV_{vi} \times PV_{di}} \quad (2)$$

PV_{vi} is the preferential value for velocity i and PV_{di} is the preferential value for depth i.

The third criterion was the average habitat area with a HSI greater than a selected value, thus indicating a highly suitable habitat area in the studied reach (HSA) Eq. (3).

$$HSA = \frac{\sum_{i=1}^{N} A_i \times (HSI_i > \tau)}{\mathrm{N}} \quad (3)$$

τ is the threshold value for HSI (0.5 for the Juvenile period and 0.7 for the spawning period)

The last criterion, the Hydraulic Habitat Suitability Index (HHS) Eq. (4) is a unitless index defined between 0 and 1. It was obtained by dividing the WUA by the total inundated area (Eq. (4)).

$$HHS = \frac{1}{\sum_{i=1}^{n} A_i} \sum_{i=1}^{n} A_i \, HSI_i = f(Q)[-] \quad (4)$$

Turbine flow optimization and environmental flow constraints

We aim to optimise the hourly hydropower turbine flow given varying electricity prices and assuming stochastic inflow to the upper reservoir such that the hydropower plant maximises annual profits. This optimization involves adjusting the turbine flow to adapt to variable river flow conditions, ensuring that the operation is as close to the design-specified optimum as possible. To account for the inflow uncertainty, Q-learning is applied for daily flow optimisation. Q-learning is a model-free algorithm, I.e., as it does not require a model of the environment (Sutton & Barto, 2018). Given the scheduled total daily flow, constrained non-linear optimisation is applied for flow allocation for each hour of the day.

For each hour-of year $t \in \{1,2,\dots,T = 8760\}$, the hydropower plant operator chooses an hourly turbine flow h_t ($m^3 s^{-1}$) such that its annual revenue is maximised. Hourly revenue r_t (€) is determined by the amount of electricity generated $q(h_t)$ (MWh) times the hourly electricity price p_t $(€/MWh)$: $r_t =$

$q(h_t)p_t$. The water level in the reservoir must be kept between the lower ($\underline{w}$) and the upper limit ($\overline{w}$). Excess water (s_t) is conveyed downstream through the spillway channel when the turbine flow h_t and evaporation e_t are insufficient to keep the water level below the upper limit $\underline{w}$. The transition dynamics of water level in the reservoir is as follows: $\underline{w} \leq w_{t+1} = w_t + \alpha(i_t - h_t - s_t) - e_t \leq \overline{w}$. Parameter α translates the flow units ($m^3 s^{-1}$) to changes in water level (cm).

In the Nordic power market, hourly prices are set in the day-ahead market, where electricity sellers submit their bids a day in advance of delivery (Spodniak et al., 2021). Accordingly, the hydropower operator is required to make decisions regarding the generation for the upcoming day before the actual inflow is known. In this context, the reinforcement learning algorithm is suitable for optimizing river management. To facilitate the optimization, we use the historical daily inflow time series data spanning the period from 2000 to 2017 as the training dataset for the reinforcement learning algorithm (shown as coloured profiles in Figure 3). This training data is used to find the optimal generation policy that maximises the average annual reward. With the learned policy, we simulated the hydropower operation based on the inflow realisation for the year 2018 (shown as the black profile in Figure 3). The model provides a practical depiction of the hydropower plant's operation context, considering the uncertainty with inflow conditions.

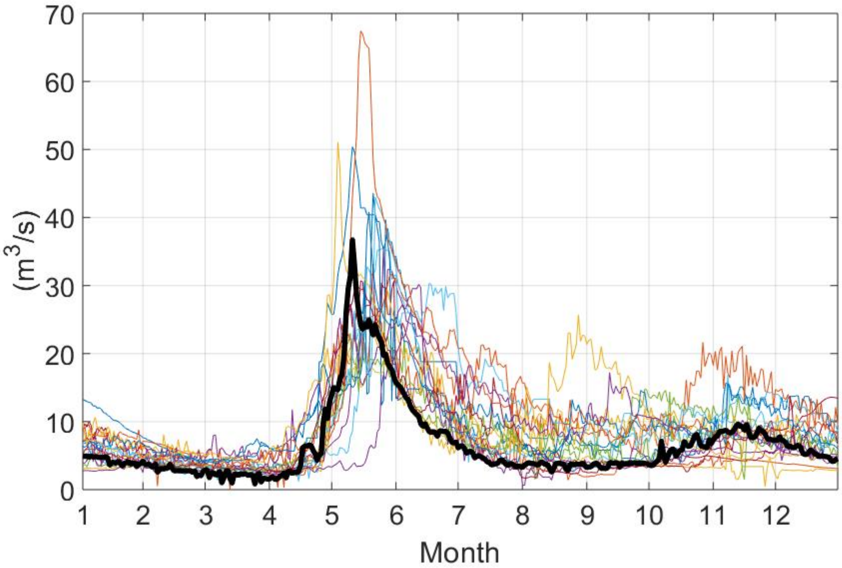

Figure 3. Annual daily inflow profiles in training data years, 2000 – 2017 (colour), and in the operation year, 2018 (black). Inflow to upper reservoir is calculated based on the water volume in Ala-Vuotunki lake and the water discharge at the Myllykoski power plant. Source: Finnish Environment Institute. Watershed simulation and forecasting system (2018).

The flow constraints are based on both technical and environmental considerations. From a technical perspective, the maximum turbine flow of the hydropower plant is $16\,m^3/s$, and the minimum flow is $0\,m^3/s$. Additionally, we set the turbine flow ramping rate to $8\,m^3/s$. The ramp rate for an average flexible hydropower plant is estimated to be roughly 20 – 30% of nameplate capacity in 15 minutes (Pahkala et al. 2018). Assuming a ramp rate of 25% of the nameplate capacity, this implies that the average hourly generation of the hydropower plant can ramp up from the minimum to the maximum level within one interval hour. In the benchmark scenario, the hydropower plant operates under these technical flow constraints. We devised three environmental flow scenarios. In scenario 1, the minimum total flow (turbine and spill flow) downstream from the hydropower dam is increased to $2\,m^3/s$. In scenario 2, total flow ramping is tightened to $\pm 0.5\,m^3/s$. Moreover, in the 3rd scenario, total flow cannot exceed $5\,m^3/s$ from mid-June to August. Environmental flow constraints (Table 1) are set based on fish habitat quality (calculated in designing the environmental flow constraints section) and ramping rate is calculated using the normalised ramping rate from a comparable, free-flowing river nearby (Oulankajoki).

$$(RR_k)_i = (\frac{\Delta Q_k}{\Delta t_k}) = (\frac{Q_k - Q_{k-1}}{t_k - t_{k-1}})_i, i \in [1{,}365] \quad (5)$$

$$RR_i = P_{90}|(RR_k)_i|; \quad (6)$$

$$RR = median(RR_i). \quad (7)$$

$$RR_{indicative} = P_{90}(RR) \quad (8)$$

RR is a dimensional parameter giving ramping rate measurements. Where subscript k is the hour of the day and |…| denotes absolute value. RR is computed as the annual median of daily values of RR_i, which is the 90th percentile (P90) of the discretised time derivative of the instantaneous streamflow series. The 90th percentile, P90, was arbitrarily chosen as a measure of the daily rate of change because it is a conservative estimation of the cut-off value for extremely high flow events and allows for the exclusion of possible error measurements. Using the absolute value of P90, ramping rates of the hydrographs in both directions, i.e., the increasing and decreasing limb, were considered. The P90 value of ramping rate from 9 years of data came out to be 0.5. If no ideal free-flowing counterpart is available, an assembled value from multiple rivers flowing in the region can also be used.

Table 1. Myllykoski hydropower environmental flow constraints at river Kuusinkijoki.

	Benchmark	**Scenario 1**	**Scenario 2**	**Scenario 3**
Minimum flow	$0\ m^3/s$	$2\ m^3/s$	$2\ m^3/s$	$2\ m^3/s$
Flow ramping	$\pm 8\ m^3/s$	$\pm 8\ m^3/s$	$\pm 0.5\ m^3/s$	$\pm 0.5\ m^3/s$
Maximum flow mid-June to August	---	---	---	$5\ m^3/s$

Results

Multi-model integration into a single framework.

We developed a framework that combines economic, hydrodynamic, and fish habitat models with estimates of cultural ecosystem services (Table 2). The first step involved coupling a 2D hydrodynamical model with a fish habitat model to estimate fish habitat conditions below the hydro dam. Secondly, river flow hydraulics that influence fish habitat conditions were evaluated, and critical habitat-based environmental flow constraints were developed. Thirdly, a novel Q-learning optimisation model was developed to regulate hydropower, considering intra-day variability in electricity prices, and the technical and environmental flow constraints identified in step two. Furthermore, revenue data from recreational visits to the river were added to the analysis to estimate the overall cost of environmental flow constraints. This approach offers a comprehensive framework to study the ecological and economic effects of environmental flow constraints.

Table 2 Hydropower Optimization Inputs, Models, and Outputs Summary

Data	**Source**	**Models**	**Prognostic variable and units**
Subdaily river flow data	SYKE[1]	HecRas 2D	River flow hydraulics (m^3s^{-1}, m^3s^{-2} and m)
River bathymetry data	Luke[2]		
Subdaily energy prices data	Nord pool[3]	Hydropower	Optimised hydropower release

Daily reservoir inflow data	SYKE[1]	optimization model	(m^3s^{-1})
Fish preference curves	Luke[2]	Casimir fish	Highly suitable habitat area (m^2)
River Visit Revenue	Local Municipality	Valuating ecosystem services	Recreational ecosystem services estimation (€)

[1]Finnish environment Institute; [2]Natural Resource Institute Finland; [3]Nord Pool Spot

Designed environmental flow constraints.

Recreational fishing is an important ecosystem service along rivers, and hydropower activities can affect the habitat conditions and popularity of fishing in the area. In this study, we chose the quantity and quality of brown trout (Salmo trutta) and grayling (Thymallus thymallus) fish habitats in the downstream reach to indicate the potential of RES offered by the river. The connection between the fish habitat and recreational value is established by considering that improvements in fish habitats leads to an increase in fish abundance, attracting more people and ultimately increasing tourism revenue.

Three hourly flow characteristics, 1) minimum flow, 2) maximum flow, and 3) ramping rate, were identified as the variables affecting the quality of fish habitats. The ramping rate is determined by subtracting the flow rate at the start of the hour Q_t from the flow rate at the end of the hour Q_{t+1}. Hence, environmental constraints were designed around these three flow characteristics, based on fish habitat modelling results (see Methods and supplementary figure S1, S2 and supplementary table S1, for details of their formulation). A Habitat Suitability Index (HSI) value of 0.7 and higher was selected for highly suitable spawning habitat areas, and 0.5 or higher for juvenile habitat areas. A minimum flow threshold of 2 $m^3 s^{-1}$ was chosen in our study river to ensure that the weighed useful area (WUA) for fish is greater than 30% of the total wetted area during most of their life stages. This choice is linked to recreational value by preserving and improving habitats, thereby potentially enhancing the fishing experience and attracting more recreational activities. As a result of setting the minimum flow threshold at 2 $m^3 s^{-1}$, grayling spawning, brown trout spawning, and grayling juveniles experienced an average WUA gain and highly suitable habitat area (HSA) gain, while for brown trout juveniles, the gain decreased (Table 3) (Supplementary figure S1).

The maximum flow threshold of 5 $m^3 s^{-1}$ was set for juveniles from mid-June to August. This was based on an arbitrarily chosen value for the Hydraulic Habitat Suitability Index (HHS) being greater than or equal to 0.4. In choosing the maximum flow limit, priority was given to the flow preferred by brown trout juveniles, as their habitat was at the greatest risk at higher discharges (Supplementary figure S1). In an ideal scenario, a higher HHS value (e.g., 0.7) would be chosen as a threshold, but the river stretch we investigated had an HHS value of 0.58 for trout juveniles at 1 $m^3 s^{-1}$, which was less than our minimum flow limit. Grayling juveniles had an HHS of 0.63 at 5 $m^3 s^{-1}$, but the overlap with Trout juveniles led to the smaller HHS being chosen.

Table 3. Availability of good habitat areas under flow constraints at River Kuusinkijoki. Ramping rate constraints are included in all three scenarios.

Metrics	**Grayling spawning (m^2)**	**Trout spawning (m^2)**	**Grayling juveniles (m^2)**	**Trout juveniles (m^2)**
Highly suitable area with no constraint	13332.18	20834.88	14949.55	6758
Highly suitable area with min flow constraint (m^2)	15577.8	22527.73	16648.66	5792.53
Net change in area with min flow constraint	**+2,245.62**	**+2,050.85**	**+1,699.11**	**-965.47**
Change with min flow constraint	16.84%	9.84%	13.64%	-14.28%
Highly suitable area with max flow constraint	15577.80	22885.78	15624.25	10801.75

Net change in area with max flow constraint	**+2,245.62**	**+3,050.90**	**+674.70**	**+4043.75**
Change under min and max flow constraint	+17%	+10%	+5%	+60%

The economic cost of flow constraints to hydropower production

Based on environmental and technical constraints, we developed four hourly flow release scenarios to analyse their impact on the total revenue generated by the hydropower plant. Each scenario represents different combinations of flow constraints (for a detailed description of each scenario, see the methods section and Table 1). To illustrate the flow profiles under different scenarios, Figure 4 displays the total flow profiles (turbine and spilling flow) for each hour-of-year in three scenarios: the benchmark scenario (flow under no environmental flow constraints), and two environmental flow scenarios, denoted as scenario 1 and scenario 2. In environmental flow scenario 1, the minimum flow requirement of 2 m^3s^{-1} (represented by the horizontal grey line) is successfully met throughout the annual period, ensuring the necessary minimum environmental flow for the river. In environmental scenario 2, with a tightened ramping rate, the minimum flow threshold is occasionally broken during the low inflow period, which extends from the end of February to the beginning of April. Due to the incoming inflow peak in the spring, the water level in the reservoir is kept low during this period. Consequently, there will be instances when the hydropower plant cannot meet the minimum flow criterium without compromising the minimum water level in the upper reservoir. This situation creates a trade-off between meeting the tightened flow ramping constraints and maintaining the minimum flow requirement during the low inflow season.

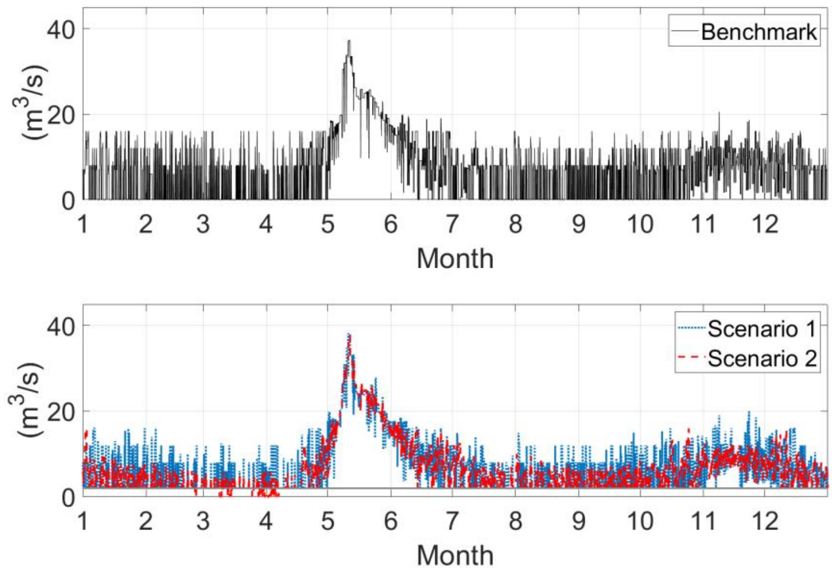

Figure 4. Simulated hourly total (turbine and spilling) flow in benchmark scenario (top) and environmental flow scenarios 1and 2 (bottom). The grey line marks the minimum flow constraint in scenarios 1 and 2.

In environmental flow scenario 3, the hydropower plant faces a challenge in meeting the maximum environmental flow criterion of 5 m^3s^{-1} during the period from mid-June to August, without exceeding the upper water level constraint of the reservoir (Supplementary Figure S4, supplementary material). Consequently, if the environmental regulator aims to maintain the flow level within the specified limits in environmental flow scenario 3, it will require relaxing the water level constraints of the upper reservoir. This issue constitutes a separate environmental flow optimization problem, involving a trade-off between maximum flow and water level variability. Although we have opted not to include scenario 3 in our subsequent analyses due to this site-specific limitation, we believe it's important to present this scenario. In other contexts, this scenario might be relevant, and the limitations we encountered may not be applicable. Next, we focus on the results from environmental flow scenarios 1 and 2.

Environmental flow limits restrict the hydropower plant’s ability to allocate turbine flow based on electricity price variation (Díaz-González et al., 2016). On average, electricity prices exhibit higher values during the day and lower values at night (Figure 5, top). In contrast to the average turbine flow allocation observed in the benchmark scenario, the flow constraints applied in the environmental flow scenarios cause the hydropower plant to increase the flow during night-time and decrease it during daytime hours (Figure 5). As a result, the average revenue per unit of generated hydroelectricity decreases in the environmental flow scenarios.

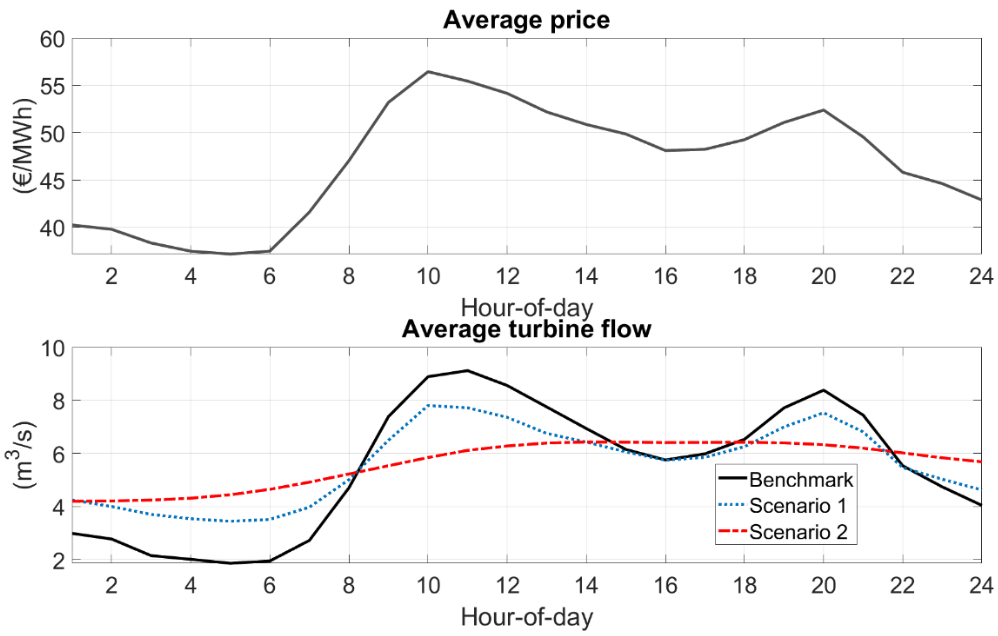

Figure 5. The daily average hourly price profile in 2018 (top) and simulated daily average hourly turbine flow profiles in the benchmark and the environmental flow scenarios 1 and 2 (bottom).

Environmental flow restrictions result in a decrease in annual hydropower revenue by 29,587 € (-14.5 %) in scenario 1 and 33,791 € (-16.6 %) in scenario 2 (Table 4). The revenue losses stem from two main factors. Firstly, flow restrictions limit the flexibility of turbine flow, resulting in a diminished average revenue from hydroelectric generation due to a loss in power, as less water is available for conversion to electricity (see Figure 5). Secondly, these restrictions also incur a decline in the average turbine efficiency (not to be confused with capacity factor) as depicted in supplementary figure S3. Due to the enforced allocation of a minimum flow of 2 m^3s^{-1} during low price hours, the turbine operates at suboptimal flow rates, affecting both its efficiency and the overall energy output.

Table 4. Simulation results for operation year 2018.

	Benchmark	**Scenario 1**	**Scenario 2**

Total revenue (€)	204 141	174 554	170 351
Revenue loss (€)	---	29 587	33 791
Total generation (MWh)	4 181	3 729	3 787
Average turbine efficiency (%) in hours when generating	88.72	48.08	64.63
Average revenue per energy generated (€/MWh)	50.11	48.08	46.22

The economic costs associated with environmental flow restrictions can vary from year to year due to natural variations in the annual dam inflow. In 2018, the total inflow was 206.5 $Mm3$, while the average inflow from 2000 to 2017 was 282.6 $Mm3$, indicating that the operation year 2018 was a drier year compared to the average. To assess the sensitivity of hydropower revenue loss, we utilize the results obtained from the training data years (2000-2017) and compare these results to the revenue loss estimate for the year 2018. Table 5 shows that the revenue loss estimates for 2018 represent the high end of the spectrum. This suggests that environmental flow regulation in scenarios 1 and 2 has a more significant impact on hydropower plant revenue during years that are drier than average.

Table 5. Total inflow and revenue loss in the operation year, 2018, and training years, 2000 – 2017.

	Operation year, 2018	**Training years, 2000-2017**		
		Average	**Max.**	**Min.**
Inflow (Mm^3)	206.5	282.6	385.6	187.2
Scenario 1, Revenue loss (€)	29 587	17 217	28 201	1 172
Scenario 2, Revenue loss (€)	33 791	21 405	33 815	9 215

Recreational ecosystem services estimation

There are three rivers that form the Ruka-Kuusamo catchment area: Kuusinkijoki, Oulankajoki and Kitkajoki. According to previous studies, the area receives about 5,400 visits from angling tourists every year, generating around 240€ of revenue per visit (Kuosku et al., 2014). These anglers support the local economy and employment during their visit by purchasing fishing permits, lodging, food, fuel, and various other services. Based on the estimated revenue loss of hydropower plants under the designed constraints (29 587€ in Scenario 1 and 33 791€ in Scenario 2; see Table 3) and a tourism revenue of 240€ per visit, an additional 123-141 fishing trips are required to compensate for hydropower revenue loss. It's crucial to highlight that this compensation refers to an economic balance in the local economy and not a direct compensation to the hydropower operators. The hydropower sector bears the loss, while the local tourism-related businesses stand to gain.

While a precise estimate of the visitors who specifically come to the region to fish on the Kuusinkijoki river is not available, it is reasonable to assume that the three rivers in the area share visitors equally. By assuming equal shares of visitors among the three rivers (33% each), the number of visitors would need to increase by 7% to 8% in order to compensate for the reduction in revenue caused by the restricted hydro power operation. Even though this increase is not derived from a detailed economic model, it still provides a valuable conceptual understanding backed by a quantitative approach. This approach simplifies the monetary valuation of the gains in river ecosystem services under optimized water allocation for stricter environmental considerations in the region.

Discussion and Conclusion

A hydropower regulated river management decision that fails to consider ecological and economical needs together, can compromise the river's ecological integrity and lead to unsustainable energy production. This study aims to quantify the cultural ES gained by optimising hydropower plant operation under inflow uncertainty. We have developed a quantitative predictive tool to evaluate the impact of hydropeaking-induced flow regime alterations on river ES. The environmental effects of small hydropower (SHP) dams can be significant and can further inflate when under increasing pressure to provide balancing energy to the market (Jager et al., 2022). The framework presented and tested here uses advances in decision making algorithms to provide a sustainable water allocation tool for SHP operation.

The ability of hydropower plant to meet peak demand is more valuable (in terms of price per energy generated) than that of technologies that provide baseload electricity with an even generation profile. We show that in the benchmark scenario, the average revenue per energy generated is 50.1 (€/MWh), which exceeds the average electricity price of 46.8 (€/MWh). In environmental flow scenario with increased minimum flow (Scenario 1), hydropower revenue decreases to 48.1 (€/MWh), but it remains above the average electricity price. This implies that the hydropower plant can adjust its generation according to the needs of the electricity system better than baseload technology. In Scenario 2, with higher minimum flow constraint and tightened flow ramping constraint, the revenue generated per energy unit is 46.2 (€/MWh), which falls below the average electricity price. This implies that the flexibility potential of the hydropower plant is reduced to such an extent that hydropower must be generated during hours with lower prices than average. Upgrading to more efficient turbines suited to the environmental flows designed for the plant may enhance energy generation efficiency (Garrett et al., 2023). Further research could provide insights into achieving sustainable and economically viable hydropower generation through optimal turbine selection.

Previously, forecasting techniques have been used for dam design, flood control, irrigation, and strategic dam planning (Anghileri et al., 2016b; Bertoni et al., 2021; Raso et al., 2014; Zhao et al., 2014). The applied optimization model we have presented here offers a practical representation of the inherent uncertainty in inflow, as the day-ahead turbine flow scheduling is conducted prior to the actual realization of daily reservoir inflow. By assessing the revenue loss within the framework of historical data spanning multiple years, we can gain insights into the impact of environmental flow restrictions on the operational performance of the hydropower plant under varying hydrological conditions. Considering knowledge from a broad range of disciplines, the framework could be implemented to mitigate the effects of river regulation, especially hydropeaking.

Small hydropower river systems could be designed anywhere using the proposed method. However, local river properties and constraints must be considered. According to our analysis, the costs of implementing environmental flow restrictions to Myllykoski SHP are recoverable through the gains in cultural ES. The provision of better habitats for fish species due to environmental flow constraints reduces hydropower revenues. However, it also has positive economic impacts as recreational fishing may increase. Previous studies have found that the number of fishing trips per angler is strongly affected by the angler’s previous catch in the area (Pokki et al., 2018).

In scenarios where environmental flow conditions are set through the tightening of minimum flow and flow ramp constraints (scenarios 1 and 2), an annual increase of 7% to 8 % in recreational fishing visits is required to compensate for the revenue loss from hydropower. It is important to highlight that we considered only direct regional economic impacts. If the indirect impacts had been included in the analysis, the regional economic impacts of recreational fishing would have been greater, relatively, than those of electricity production because the tourism sector is likely to use more intermediate inputs and generate more wage income for consumption than the hydropower sector in the area (Mustajoki et al., 2011). Thus, the growth of highly suitable fish areas may be sufficient to compensate for loss (or even to increase the regional economic impact). For the SHP under investigation, we proposed scenario 2 as the optimum management regime (a minimum annual flow of 2 m^3s^{-1} and ramping rate constraint of 0.5 $m^3s^{-1}h^{-1}$), resulting in the maximum possible gain in HSA with only a small increase required in recreational visits to the Kuusinkijoki site when compared to scenario 1. Although a detailed representation of the electricity prices, river hydrodynamics, and ecosystem services is implemented, some uncertainties, such as bed substrate and river specific ecosystem calculations, are not explored. In addition, the employed hydropower flow optimization algorithms allow the flow ramping constraints to be breached during a minor fraction of operation hours (see Supplementary Information). Despite these limitations, our framework provides a significant step forward and can be applied to a wide range of river systems with varying levels of background data.

In conclusion, at our study site the economic losses due to well-designed environmental flow constraints limiting the ecological impacts of hydropeaking by a SHP appear to be relatively small compared to the potential benefits for ecosystem services. Our study confirms that in modern society energy production using SHPs might not be the most cost-effective way to produce electricity, especially when ecosystem services benefits are considered. SHPs might have local electricity production benefits, but in transitioning to renewable energy, benefits and negative impacts needs to be evaluated simultaneously. For this need we developed and tested, a framework and method using a single case study, and showed its potential to reveal SHPs cost-efficiency from different perspectives. Especially our novel energy market model, that includes day-a-head market situation, allowed us to analyse market value of hydropeaking and to compare it with value of ecosystem services. However, the results will need to be validated for a larger number of cases, both locally and globally. This framework is only a starting point, and it can be modified and adapted to various types of hydropower plants. The results presented in the study should be considered indicative only to sites that exhibit topographical, hydrological, and climatological characteristics like those of the study site presented in this study.

Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception, design and modelling: Faisal Bin Ashraf, Hannu Huuki, Hannu Marttila; data collection: Faisal Bin Ashraf, Hannu Marttila, Ali Torabi Haghighi; River flow hydraulics and fish habitat analysis and interpretation of results: Faisal Bin Ashraf, Ali Torabi Haghighi, Juutinen Artti, Atso Romakkaniemi, Hannu Marttila; interpretation of Economic modelling results: Hannu Huuki, Juutinen Artti; draft manuscript preparation: Faisal Bin Ashraf, Hannu Huuki. All authors reviewed the results and approved the final version of the manuscript.

Open Research

This section outlines the compliance of our research with the FAIR (Findable, Accessible, Interoperable, and Reusable) Data guidelines, ensuring transparency and accessibility of the data and software used in our study.

Data and Software Availability Statement

The MATLAB scripts and associated data, crucial for replicating and understanding the findings of our study, have been archived in accordance with the FAIR guidelines (Huuki, 2023) . The following details provide direct access and citation information:

- Zenodo Archive: Access the archived data and code via https://zenodo.org/records/10155706 [Dataset and Script].
- GitHub Repository: For development history and version control details, visit https://github.com/hannuhuuki/SHP [Computational Notebook].
- The fish preference curves, are exclusively provided in the supplementary material accompanying this publication.

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