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RESEARCH ARTICLE

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The economic cost of hydropower environmental constraints under decreasing price volatility

Hannu Huuki[1,2] | Santtu Karhinen[2] | Faisal Bin Ashraf[3] | Ali Torabi Haghighi[4] | Hannu Marttila[4]

[1]Department of Economics, Accounting and Finance, University of Oulu Business School, Oulu, Finland

[2]Finnish Environment Institute, Oulu, Finland

[3]Stockholm Environment Institute, Stockholm, Sweden

[4]Water, Energy and Environmental Engineering Research Unit, University of Oulu, Oulu, Finland

Correspondence
Hannu Huuki, Department of Economics, Accounting and Finance, University of Oulu Business School, Oulu, Finland.
Email: hannu.huuki@oulu.fi

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Abstract

Hydropower operation optimization in river systems involves market prices, technological constraints affecting the efficiency of turbines, and flow constraints set by an environmental regulator. Comprehensive environmental flow regulation includes the ecological state of a river system and the impact on hydropower value. This article studies the impacts of environmental constraints on hydropower value under varying electricity price volatility scenarios. The effects of maximum flow, minimum flow, and flow ramping constraints are studied analytically and quantitatively. We frame the lost hydropower value as the economic cost of these constraints. We show that the economic costs of the environmental constraints decrease with lower price volatility. We use a marginal cost and marginal benefit framework to illustrate that the optimal flow constraint should be tightened if the price volatility decreases in the electricity market. Our approach illustrates how electricity price volatility influences the analysis of optimal environmental constraints in regulated river systems. Finally, we analyse the effect of different environmental flow release options in fishways on the economic cost of a fishway. If the hydropower operator can optimize the fishway flow allocation, then the loss in hydropower value is lower than under a constant fishway flow.

KEYWORDS
electricity prices, environmental regulation, hydropeaking, hydropower

1 | INTRODUCTION

Hydropower is a flexible power resource that helps to maintain the balance between electricity demand and supply in power systems (Gaudard & Romerio, 2014). Adjusting the power output to rapidly changing electricity demand typically results in hydropeaking, which is the discontinuous release of turbines water due to energy demand peaks. It causes artificial flow fluctuations over short-time scales downstream of hydropower reservoirs. Hydropeaking causes stress to river ecosystems and can hamper the river corridors' ecosystem services and recreational possibilities. Due to the high levels of hydropeaking observed, for example, on major Nordic rivers, there is a clear need for an integrated economic and ecological framework to regulate hydropower operations (Ashraf et al., 2018).

Short-term flow regulation can cause homogenization of river system flow dynamics, adversely affecting aquatic biodiversity (Dynesius & Nilsson, 1994; Haghighi, Marttila, & Kløve, 2014; Mustonen et al., 2016; Poff, Olden, Merritt, & Pepin, 2007). Flow conditions influence the temporal and spatial variabilities of biotic communities (Poff & Ward, 1989). Hydropeaking can be detrimental to the integrity of river ecosystems (Pellaud, 2007), causing juvenile fish mortality (Casas-Mulet, Saltveit, & Alfredsen, 2016), stranding (Nagrodski, Raby, Hasler, Taylor, & Cooke, 2012), habitat deterioration (Boavida, Santos, Ferreira, & Pinheiro, 2015), changes in fish behaviour (Vollset, Skoglund, Wiers, & Barlaup, 2016), and loss of riparian plants (see Bejarano, Jansson, & Nilsson, 2017 for a review). Hydropeaking also affects the thermal regimes (water temperature) of rivers (Dickson, Carrivick, & Brown, 2012; Ward & Stanford, 1979), water quality (Rossel & de la Fuente, 2015), and river morphology (Vanzo, Zolezzi, & Siviglia, 2016). The impacts of hydropeaking are not restricted to river ecosystems, but there are also negative effects on landscape and recreational values (Grilli, Balest, De Meo, Garegnani, & Paletto, 2016; Hastik et al., 2015).

The negative impacts of dams and hydropower operation on migratory fish have recently received much interest. Soininen, Belinskij, Vainikka, and Huuskonen (2018) discuss both the legal and the scientific drivers towards restoring ecological flows in constructed rivers. The EU Water Framework Directive requires all inland water of member state to achieve good ecological status (Voulvoulis, Arpon, & Giakoumis, 2014). Thus, the EU member states must re-evaluate the water management permits to meet the good ecological status. Also, scientific research has changed the view towards fisheries compensation. The scientific evidence of the harmful genetic impacts of hatchery rearing on fish (see Soininen et al., 2018 for a literature review) should lead to a re-analysis of the current compensation policies. Consequently, using fishways as a compensation mechanism for the impact of the hydropower plants on fisheries is gaining more attention.

The negative externalities of hydropeaking should be internalized in hydropower output optimization. Still, a damage function is rarely included in hydropower optimization models because the negative environmental impacts are hard to quantify (Edwards et al., 1999). Instead, the negative externalities are internalized in hydropower operation through flow constraints set by an environmental regulator. The cost of environmental flow regulation is defined as the lost value of hydropower generation in power markets. For instance, Harpman (1999) defines the economic value of an existing hydropower plant operation as equal to the additional costs avoided by the hydropower generation. As a result, the economic value of hydropower varies as a function of the marginal cost of maintaining the power balance. In other words, the economic cost of environmental regulation is system specific. During a high-demand period, the value of hydropower output is high because hydropower output replaces high-cost thermal generation. Conversely, the value of hydropower is low if cheaper baseload generation is sufficient to match the demand in an off-peak period.

The growing contribution of variable renewable energy sources in energy markets increases the market value of flexible hydropower generation (Hirth, 2016). However, flexible electricity demand resources may emerge in future electricity markets. Smart grids' information and communication technologies enable electricity consumption to react to the price signals in electricity markets (Haider et al., 2016). Consumers can already opt for a real-time pricing contract with hourly varying electricity prices (Huuki, Karhinen, Kopsakangas-Savolainen, & Svento, 2020). Smart metre penetration rate in Finland is high (European commission, 2021) and smart metering leads to opportunities to shift consumption from peak hours to off-peak hours (Nordic transmission system operators, 2015). The increased demand-side flexibility can lead to reduced electricity price volatility, if the difference in electricity load decreases between the peak and the off-peak periods.

Previous studies have evaluated the interaction between power market and regulation practices (Haghighi et al., 2019) and evaluated the economic cost of hydropower flow constraints. Harpman (1999) compares the historical flow data to the simulated Modified Low Fluctuating Flow alternative in Glen Canyon Dam and found that the economic cost of the modified flow was 9% on an annual basis. Edwards et al. (1999) showed the effect of minimum release and ramping constraints on the hourly hydropower allocation theoretically and by simulating the hydroelectric generation of the Flaming Gorge facility in Utah. Compared to baseline, the minimum release constraint increased the costs of providing power by 14%. Combined minimum and ramping constraints, on the other hand, increase the costs by 15%. Niu and Insley (2013) simulate the hydro production of a prototype plant in Ontario. They found that ramping constraints decreased hydropower profits in the range of 2% to 8%. Furthermore, Niu and Insley (2016) showed that the effect of ramping restrictions was conditional on the variation in prices. Perez-Diaz and Wilhelmi (2010) used a hydropower plant in the Northwest of Spain as a case study. Their results indicated that the effects of minimum flow and maximum ramping rate constraints were strongest in the intermediate mean daily flow region, where the plant operator had the greatest flexibility in water use. A comprehensive study, which evaluates the economic costs of environmental constraints on hydropower under varying electricity price volatility levels is currently lacking.

We contribute to the literature by evaluating the economic costs of environmental constraints on hydropower under reduced electricity price volatility. We model the effect of a maximum flow constraint, a minimum flow constraint, and a ramping flow constraint on the value of hydropower generation. Additionally, we consider a fishway flow requirement in the model. Our framework is as follows: First, we theoretically study the effects of environmental constraints. Second, we quantify the effects of tighter operation constraints on the hydropower plant's profits by simulating the optimal turbine flow and fishway flow over a weekly period for a prototype hydropower plant. The results are used to illustrate the principle of setting an optimal environmental constraint level.

2 | MODEL FORMULATION

The model formation is based on three assumptions. Firstly, we assume that the hydropower plant operator maximizes profits by optimizing its output based on hourly electricity price p_t. Time is discrete and hours are indexed by $t = 1, \ldots, T$. The second assumption is that the plant's generation capacity is small in relation to the whole power system's size. This assumption allows us to treat the hydropower plant as a price-taker so that changes in its output do not affect the market price. Finally, the hydropower plant operates under perfect foresight with respect to water inflow and electricity prices.

Hydropower plant operation is illustrated in Figure 1. The operator has two options to allocate water R from the reservoir. Water can be run through a turbine, where water flow h_t is transformed to power output $q(h_t)$. Alternatively, water can be allocated to a fishway. The fishway flow f_t serves as an attraction and allows migratory fish species to bypass hydropower dams (Williams, Amstrong, Katopodis, Larinier, & Travade, 2012), and provides cultural ecosystem services (Krchnak, Richter, & Thomas, 2009). The combination of turbine flow and fishway flow forms the total downstream flow $(h_t + f_t)$.

Equations (1)–(7) present the deterministic dynamic optimization problem.

$$\max_{h_t, f_t} \sum_{t=1}^{T} p_t q(h_t) \tag{1}$$

subject to

$$\sum_{t=1}^{T} (h_t + f_t) \le R \tag{2}$$

$$0 \le h_t \le \overline{h}, t = 1, \ldots, T \tag{3}$$

$$\sum_{t=1}^{T} f_t \ge F \Longrightarrow -\sum_{t=1}^{T} f_t \le -F \tag{4}$$

$$\underline{f} \le f_t, t = 1, \ldots, T \tag{5}$$

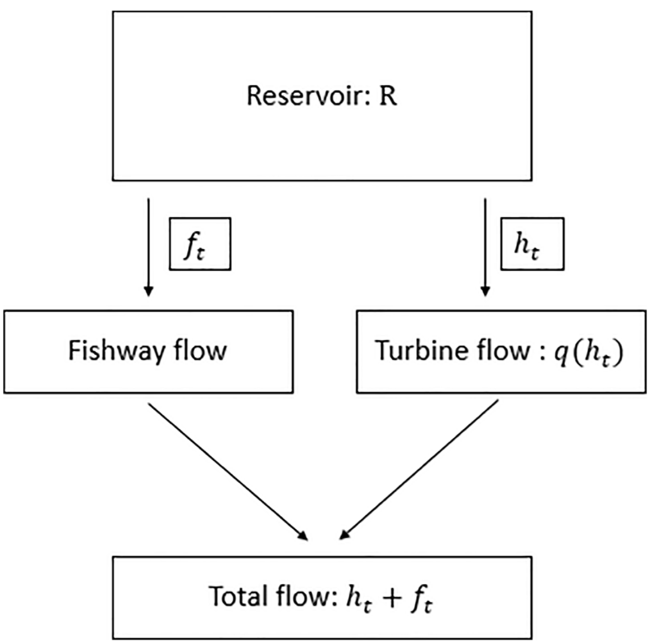

FIGURE 1 Hydropower plant illustration

$$\underline{flow} \le h_t + f_t \le \overline{flow}, t = 1, \ldots, T \tag{6}$$

$$\underline{r} \le h_t + f_t - h_{t-1} - f_{t-1} \le \overline{r}, t = 2, \ldots, T \tag{7}$$

The hydropower plant maximizes revenue $p_t q(h_t)$ (Equation 1) under physical constraints related to the water mass in the reservoir R (Equation 2) and maximum turbine flow $\overline{h}$ (Equation 3), where revenue equals profits as variable costs for hydropower are assumed to be zero. Furthermore, the plant operates under the following constraints set by the environmental regulator:

- total fishway flow over period $t = 1, \ldots, T$: F (Equation 4)
- minimum fishway flow: $\underline{f}$ (Equation 5)
- minimum and maximum total flow: $\underline{flow}$ and $\overline{flow}$, respectively (Equation 6)
- minimum and maximum total flow ramp rate: $\underline{r}$ and $\overline{r}$, respectively (Equation 7).

The Lagrangian function and the Kuhn-Tucker conditions of the constrained dynamic optimization problem are presented in Appendix A. Next, in Section 3, we illustrate the effect of decreased price volatility on the cost of environmental constraints in a two-period framework.

3 | THEORETICAL ANALYSIS OF HYDROPOWER OPERATION CONSTRAINTS IN A TWO-PERIOD FRAMEWORK

The following section assumes a two-period $(t = 1, 2)$ electricity market framework with a supply function S and a time-varying demand D_t. The electricity demand (D_1) in the first period (peak) is higher than the demand (D_2) in the second period (off-peak). Demand is assumed to be vertical, that is, perfectly inelastic. The supply function describes a merit order curve of the electricity market, where electricity generation plants are ordered by their marginal costs from lowest to highest. Equilibrium prices p_1 and p_2 are set at the crossing points of demand and supply. Given the increasing supply function, higher demand implies higher electricity price: $D_1 > D_2 \Longleftrightarrow p_1 > p_2$. Next, assume that the electricity demand in the peak period decreases $(D_1^r < D_1)$ and demand in the off-peak period increases $(D_2^r > D_2)$. This leads to a reduced (r) price difference between the peak and off-peak periods: $(p_1 - p_2) = \Delta p > (p_1^r - p_2^r) = \Delta p^r$. This assumes that the average price $(\overline{p})$ remains unchanged: $p_1 - p_1^r = p_2^r - p_2$.

We analysed the economic costs of environmental constraints in this two-period framework. We derived the costs related to the maximum flow, the minimum flow, and the flow ramping constraints in Section 3.1. In Section 3.2, we derive the cost of the fishway flow. We separate a constant fishway flow requirement and a total fishway flow requirement. We assume a linear transformation from flow h to power $q(h)$. Thus, the marginal effect of change in flow to power output is constant: $dq(h)/dh = q'$. For the derivation of the results, see Appendix B.

3.1 | Flow constraints

The cost of maximum flow restriction is derived by assuming that the hydropower plant maximizes profits (Equation 1), given the total resource constraint (Equation 2) and the flow constraints (Equation 6) in the two-period framework ($T = 2$). Because $p_1 > p_2$, we can assume that the hydropower plant allocates production to the first period as much as the maximum flow constraint $\overline{flow}$ allows. Thus, the maximum flow constraint binds in the first period: $\sigma_1 > 0$. The first-order conditions for the constrained optimization problem yield the following equation for the shadow cost of the maximum flow restriction:

$$\sigma_1 = \Delta p q' \tag{8}$$

A tighter constraint for the maximum flow forces the hydropower plant to allocate production from high-price to low-price periods. Equation (8) shows that the cost (reduced hydropower value) of the policy is the price difference Δp times the transformation of change of flow in power units q'. Notably, the cost of this policy decreases with lower price volatility. When the price difference decreases ($\Delta p^r < \Delta p$), the cost of maximum flow restriction decreases accordingly:

$$\sigma_1^r = \Delta p^r q' < \Delta p q' = \sigma_1 \tag{9}$$

The cost of ramping flow restriction is derived by assuming that the hydropower plant maximizes profits (Equation 1), given the total resource constraints (Equation 2) and the ramping constraints (Equation 7) in the two-period framework ($T = 2$). Because $p_1 > p_2$, it can be assumed that the hydropower plant allocates production to the first period as much as the down ramping constraint $\underline{r}$ allows. Thus, the minimum ramping constraint binds: $\alpha_2 > 0$. The first-order conditions show the shadow cost of the flow ramping restriction:

$$\alpha_2 = \frac{1}{2}\Delta p q' \tag{10}$$

Tightening the flow ramp constraint by one unit forces the hydropower plant to transfer half a unit of flow from the high-price period to the low-price period. Equation (10) shows that the cost of this policy is half the price difference times the change of flow in power units q'. Reduced price volatility ($\Delta p^r < \Delta p$) implies lower cost of flow ramp constraint:

$$\alpha_2^r = \frac{1}{2}\Delta p^r q' < \frac{1}{2}\Delta p q' = \alpha_2 \tag{11}$$

3.2 | Fishway flow requirement

The cost of total fishway flow requirement is derived by assuming that hydropower plant maximizes profits (Equation 1), given the total resource constraints (Equation 2), the total fishway flow requirement (Equation 4), the minimum fishway flow constraint (Equation 5), the total flow constraints (Equation 6), and the ramping constraints (Equation 7) in the two-period framework ($T = 2$). Because $p_1 > p_2$, the hydropower plant aims to allocate as much turbine flow to the first period as possible. Minimum fishway flow constraint restricts this decision: $\kappa_1 > 0$. Additionally, we assume that the maximum flow restriction binds in the first period: $\sigma_1 > 0$. The total fishway flow requirement binds by definition: $\mu \neq 0$. The first-order conditions yield the following equations for the shadow costs of minimum fishway flow and the total fishway flow requirements:

$$\kappa_1 = \Delta p q' \tag{12}$$

$$\mu = \lambda \tag{13}$$

Equation (12) shows that the cost of the minimum fishway flow constraint is the difference in prices times the change of flow in power units q'. If the minimum fishway flow requirement is relaxed by one unit, the hydropower plant allocates this unit of fishway flow to the second period and increases the turbine flow in the first period with a higher price. The shadow price of the minimum fishway flow requirement is lower when the price volatility decreases ($\Delta p^r < \Delta p$):

$$\kappa_1^r = \Delta p^r q' < \Delta p q' = \kappa_1 \tag{14}$$

Equation (13) implies that the shadow price of total fishway flow requirement (μ) equals the shadow price of the hydroenergy resource (λ). Consequently, from the point of view of the hydropower plant, tightening the total turbine passing flow constraint is the same as reducing the hydropower reservoir content.

The equality between μ and λ (Equation 13) changes if, instead of the maximum flow, the binding constraint in the hydropower allocation is the down ramping constraint. Then, the shadow price of the down-ramping constraint $\alpha_2 > 0$ (see Equation 10) decreases the shadow cost of the total fishway flow requirement:

$$\mu = \lambda - \alpha_2 < \lambda \tag{15}$$

If the ramping constraint is binding in the optimal allocation decision, the fishway flow can be used to slack the allowed turbine flow changes. Equation (15) shows that in the case of binding ramping constraints, tightening the requirement for total fishway flow does not affect the hydropower plant's profits to the same extent as the reduction of hydropower reserve.

Next, Section 4 presents the prototype hydropower plant parameters, electricity price data, and flow constraint scenarios. The simulation results in Section 5 illustrate how the theoretical two-period model results are realized over a one-week period.

4 | SIMULATION

4.1 | Prototype hydropower plant

The prototype hydropower plant data are based on the Taivalkoski hydropower plant, which is located along river Kemijoki in the Northern Finland. Data consist of the average hourly flow, $flow_t$ (m^3/s), for

TABLE 1 Hydropower operation constraints in the benchmark scenario and in the environmental policies

	Benchmark	Environmental policies			
Max. flow (m^3/s)	**726**	**672**	**617**	**563**	**508**
Min. flow (m^3/s)	101	156	210	264	319
Flow ramping (m^3/s)	∓438	∓405	∓372	∓339	∓307

the period second October to eighth October in 2017 (Finnish Environment Institute, 2017). The sample period with mean flow of 473 (m^3/s) represents well the average flow of 483 (m^3/s) during the period[1] from September to April. Total water resource R (m^3) available for the hydropower plant within the one-week simulation period is set to equal the realized total flow of the prototype plant: $R = \sum_{t=1}^{T} \text{flow}_t = 286.1 \cdot 10^6 \, m^3$, $T = 168$.

Hydropower generation q_t (MWh/h) in hour t is calculated as

$$q(h_t) = (\eta \cdot \rho \cdot g \cdot H \cdot \text{flow}_t) 10^{-6} \tag{16}$$

where ρ is the water density (kg/m^3) and g is the acceleration of gravity constant $(9.81 \, m/s^2)$. The head height H of the plant is 15 m, and the efficiency factor η of the Kaplan turbine is set to a constant value of 0.85. Hydropower turbine efficiency varies with the discharge. Due to the lack of technical data, we simplify the efficiency to represent the high range of turbine efficiency from technical documents. The generated power in watts (W) is converted to megawatts (MW).

The benchmark hydropower operation constraints are based on the realized hourly flow of the prototype hydropower plant (Table 1). The flow constraints are then tightened in four steps in each environmental policy scenario. The maximum hourly flow ($\overline{\text{flow}}$) is decreased by 54 m^3/s (7.5%) in each step (maximum 30% reduction in the tightest policy). Similarly, the minimum hourly flow ($\underline{\text{flow}}$) is increased by 54 m^3/s in each step. In the flow ramping policies, the up-and down-ramping constraints ($\underline{r}$ and $\bar{r}$) are tightened by 33 m^3/s (7.5% reduction) in each phase.

In the fishway flow scenarios, the total flow requirement to the fishway is set to 2.5% of the total water resource R. We set two separate scenarios. First, constant hourly fishway flow f is set to 11.83 m^3/s. Second, minimum hourly fishway flow $\underline{f}$ is set to 2 m^3/s, and the total flow must meet the 2.5% of the total water resource constraint: $\sum_{t=1}^{T} f_t \geq 0.025R$. The minimum flow for the Taivalkoski hydropower plant is based on the Kemijoki fishway report (Centre for Economic Development, Transport and the Environment, 2014). In this case, the hydropower plant can optimize both the turbine flow h_t and the fishway flow f_t.

4.2 | Price regression model

Scenarios with lower price volatility describe the electricity price setting of a smart grid electricity system with automated metering and consumption optimization. It is assumed that this higher share of consumption optimization leads to load shifting, which decreases price volatility. We estimate an electricity price model to show how the electricity load shifting can decrease the electricity price volatility. Similar regression models identifying the determinants of the day-ahead market prices can be found in Gelabert et al. (2011), Woo, Horowitz, Moore, and Pacheco (2011), and Karhinen and Huuki (2019).

We hypothesize that the electricity consumption is inflexible, mainly determined by exogenous weather conditions. To support this assumption, we estimated a sample of hourly price elasticities of demand from hourly bid data provided by Nord Pool (, 2019). The elasticity estimates varied between 0.005 and 0.01 in the sample period. Nuclear power generation is treated as baseload power source, whose output is not adjusted according to the short-term variation in prices. As shown in the abovementioned literature, wind power has a decreasing impact on the day-ahead electricity prices. To avoid any endogeneity bias, special attention needs to be paid to the flexible generation sources, such as separate thermal power and hydro power. We control the effects of other thermal power generation by including the prices of oil, natural gas, and coal in the model. Water inflows to the largest lakes in the five main watersheds (Finnish Environment Institute, 2017) are used to capture the impact of hydro power on price formation. Forecasted day-ahead wind power output in Denmark, Estonia, and Sweden, as well as aggregated load in Denmark, Estonia, Sweden, and Norway, are included to capture the impact of Nordic power market conditions on Finnish area prices. Lastly, we controlled for the impact of non-available power generation capacity (failure and maintenance) on the prices. To ensure the stationarity of all variables at 5% significance level, we used first differences of nuclear, fuel prices, and water inflows in the estimation. Power market data were collected from the Nord Pool (2019) and ENTSO-E (2019) databases.

The results of the different specifications of the regression model are shown in Table 2. Model (1) quantifies the relationship between price and load when no other market conditions are controlled. Model (2) adds wind and nuclear as exogenous generation sources. Lastly, Model (3) adds all other relevant controls. The estimated load coefficients remain relatively stable across the specifications, reflecting its low correlation with the control variables. The average impact of wind on price is −3.48 €/GWh, which is comparable to the results in previous literature (see, for example, Gelabert et al. (2011)). A 1 GWh increase (decrease) in electricity demand at hour t increases (decreases) the hourly price p_t by 2.822 (€/MWh).

To formulate the price volatility scenarios, we modified the realized sample price profile so that the price peaks are cut, and the price valleys are filled until the daily price volatility is reduced by 15% and by 30%. The average price level remains unchanged at 30.98 €/MWh.

TABLE 2 Electricity price regression model

	Dependent variable: Day-ahead market price (€/MWh)		
	Model		
	(1)	(2)	(3)
Constant	12.928*** (0.648)	12.389*** (0.615)	−33.764*** (1.384)
Load	2.151*** (0.068)	2.612*** (0.066)	2.822*** (0.188)
Wind		−8.454*** (0.273)	−3.480*** (0.320)
Δ nuclear		0.283 (4.303)	0.193 (3.090)
Load in other Nordic countries	No	No	Yes
Wind power controls	No	No	Yes
Fuel price controls	No	No	Yes
Inflow controls	No	No	Yes
Unavailable capacity controls	No	No	Yes
Month-of-year controls	No	No	Yes
Day-of-week controls	No	No	Yes
Hour-of-day controls	No	No	Yes
Observations	8,760	8,760	8,760
Adjusted R^2	0.102	0.191	0.588

*$p < .1$. **$p < .05$. ***$p < .01$.

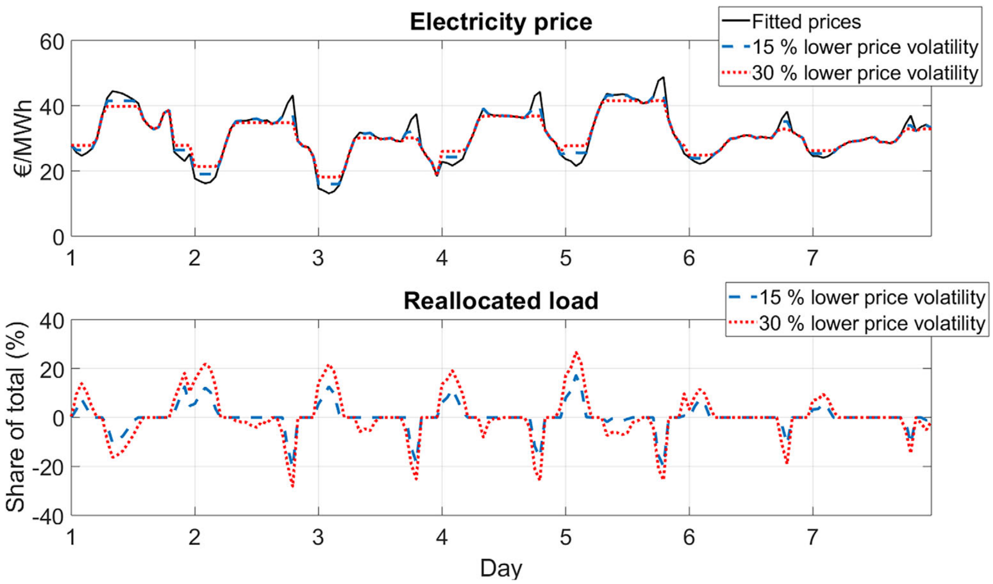

FIGURE 2 Electricity price profiles and reallocated load profiles for the electricity price scenarios [Color figure can be viewed at wileyonlinelibrary.com]

The top graph in Figure 3 shows the fitted and modified price profiles over the period 2.–8.10.2017. The bottom graph of Figure 2 shows the share of reallocated load needed to achieve the reductions in price volatility. On average, the required load-shifting share represents 7.0% of total load in the 15% price volatility reduction scenario and 9.8% of total load in the 30% price volatility reduction scenario.

The analysis focuses on hydropower optimization considering only the hourly prices in the day-ahead electricity market. Intra-hour balancing markets would incentivize the hydropower plant to offer short-term ramping services to the power grid. Typically, compensation from operations in intra-hour balancing power market is higher than in the day-ahead market, which could alter the optimal flow allocation. Additionally, wind power capacity is kept constant across the scenarios. A higher share of variable renewable energy could change the price profile and affect the costs of environmental constraints. However, it remains unclear what is the net price impact of variable electricity generation when both day-ahead and balancing markets are considered.

5 | RESULTS

5.1 | The effects of the flow constraints on the turbine flow allocation

Flow constraints change the optimal turbine flow profile. Impacts of tighter maximum and minimum flow constraints on the hydropower turbine flow allocation are shown in Figure 3. A direct effect of a tighter maximum flow constraint (middle graph) is that less water can be run through turbines during the high price periods (see top graph). The hydropower plant loses revenue, because the plant cannot utilize the hours when the value of electricity is high to the same extent as in the benchmark case. Moreover, the hydropower plant no longer reacts to smaller intra-day price variations. The effect of a tighter minimum flow constraint (bottom graph) is that more water must be run through turbines during the low-price periods. In this case, the plant operator can still use the maximum turbine flow during the high-price hours. However, to meet the minimum flow constraint, the hydropower plant must reallocate part of the turbine flow away from the high-price hours to low-price hours.

The effect of a tighter flow ramping constraint on the hourly change in turbine flow is illustrated in Figure 4. For clarity, only the

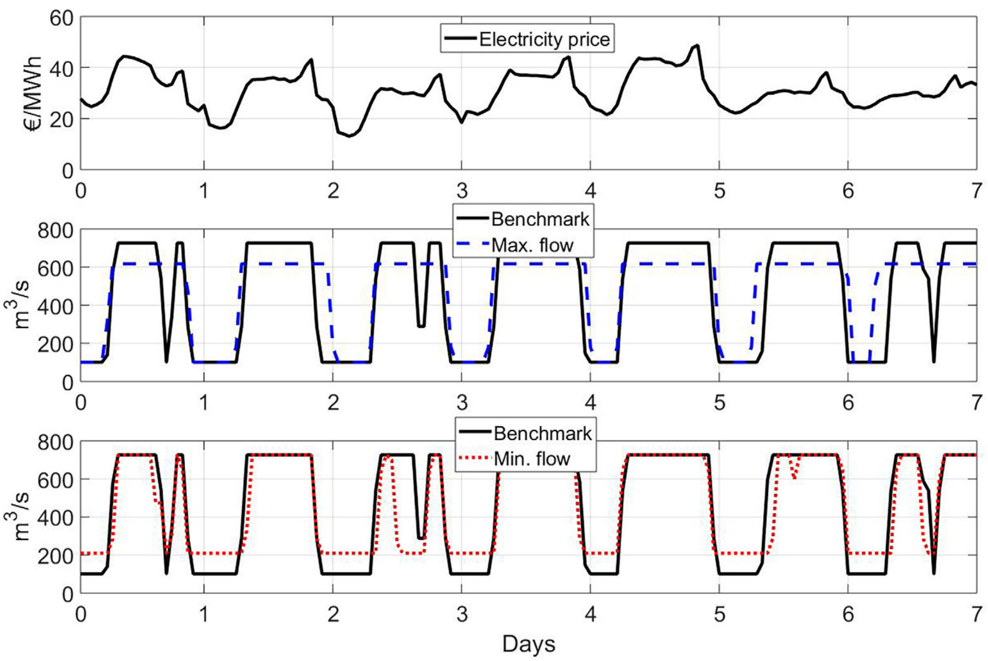

FIGURE 3 Hourly electricity price (top) and hydropower turbine flow (middle, bottom) over a weekly period. Scenarios: benchmark (black solid line), tightened maximum flow restriction (blue dashed line), and tightened minimum flow restriction (red dotted line) [Color figure can be viewed at wileyonlinelibrary.com]

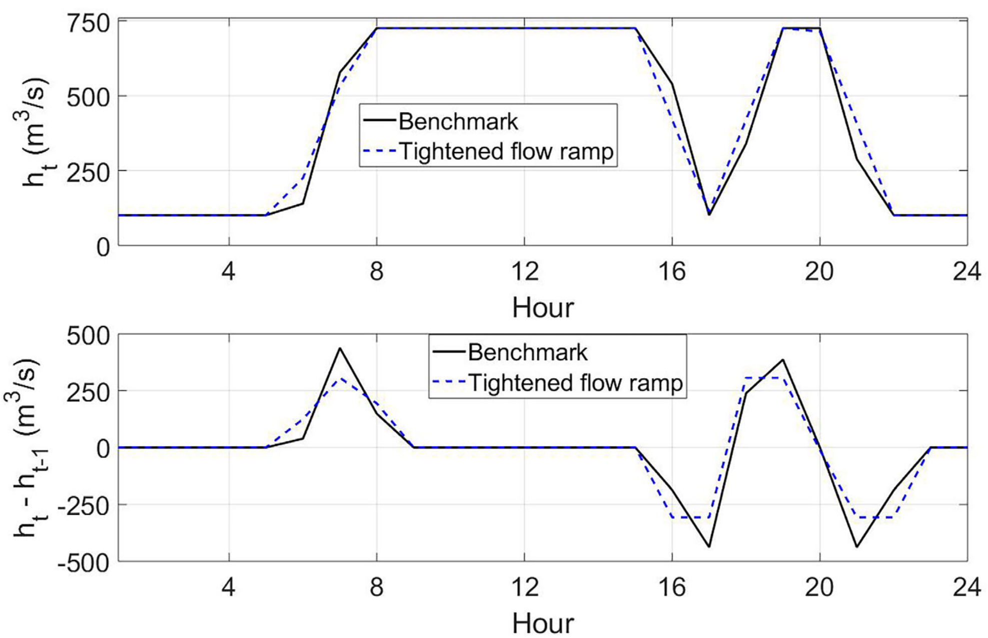

FIGURE 4 Turbine flow (top) and turbine flow ramping (bottom) in the first day of the simulated week. Scenarios: benchmark (black solid line), tightened flow ramp restriction (blue dashed line) [Color figure can be viewed at wileyonlinelibrary.com]

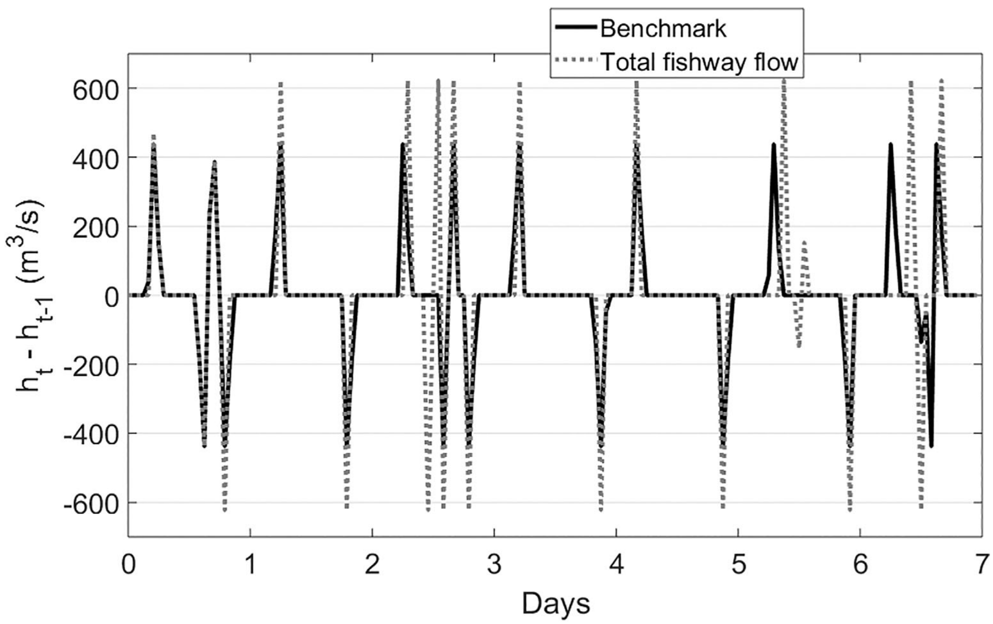

FIGURE 5 The effect of the flexible fishway flow on the turbine flow ramping range. Scenarios: benchmark (solid line), total fishway flow requirement (dashed line)

first day of the simulated weekly profile is presented. The turbine flow (h_t) profile (upper graph) shows that the hydropower plant utilizes the same hours for minimum and maximum turbine flow as the benchmark scenario. However, the ramping $(h_t - h_{t-1})$ profile (bottom graph) shows that a tightened flow ramping constraint guides the operator to allocate the up- and down-ramping events over a wider set of hours.

The effect of the fishway on the turbine flow allocation depends on the fishway flow constraints. First, the constant minimum hourly fishway requirement f flow shifts down the minimum and maximum turbine flow constraints. Thus, the turbine flow profile shape remains the same, but shifts downwards by f. Second, when there exists a possibility for fishway flow optimization, the hydropower plant allocates the fishway flow such that it has more freedom in turbine flow ramping. The hydropower plant can ramp the turbine flow (h_t) more aggressively by allocating fishway flow (f_t) to the ramping hours and still meet the ramping constraints concerning the total flow $(h_t + f_t)$. Figure 5 illustrates the increased turbine flow ramping opportunity. In the benchmark scenario, the hydropower plant exploits the whole permitted turbine flow ramping range ($\underline{r} = -438$ and $\overline{r} = 438\,\mathrm{m}^3/\mathrm{s}$). When fishway flow (f_t) is introduced as the second decision variable, the hydropower plant can loosen the turbine flow ramping constraint range to $\pm 610\,\mathrm{m}^3/\mathrm{s}$.

5.2 | The effect of flow constraints on hydropower value under decreasing price volatility

Changes in hydropower generation value related to tightened maximum (left) and minimum (right) flow constraints are shown in Figure 6. Three results stand out. First, both maximum and minimum flow constraints become less expensive for the hydropower plant as price volatility decreases. This result is in line with the theoretical analysis in Section 3. Second, the effect of a tighter flow constraint is not linear with respect to lost revenue, that is, the marginal cost of tighter environmental constraint is increasing. Third, the revenue loss of a tighter minimum flow is smaller than the loss related to maximum flow constraints. This asymmetry arises because, unlike with the maximum flow constraint, the minimum flow constraint still allows the hydropower plant to utilize the high-price hours at maximum generation capacity.

Compared to the cost of flow level constraints in Figure 6, the lost hydropower value under tightened flow ramping constraints is minor (top graph in Figure 7). The low cost of ramping constraint is due to the diurnal price profile (see Figure 2), where prices are high during the day-time and low during the night-time. Under this price regime, there is no need for several up and down turbine flow ramping events during the day. Accordingly, tightening the turbine flow ramping constraint leads only to minor decrease in hydropower value.

The decrease in hydropower value related to the fishway flow requirement is insensitive to lower price volatility (bottom graph in Figure 7). Hydropower value decreases more under the constant fishway flow requirement than under the total, flexible fishway flow requirement. This is because the hydropower producer must take the constant fishway flow as given, whereas the fishway flow can be adjusted to loosen the downstream flow ramping constraint under total flow requirement (see Section 3 and Figure 5).

5.3 | The effect of price volatility on the optimal environmental constraint level

Optimal environmental constraint levels can be derived from the analysis above. We mark the environmental constraint by c, the economic cost (lost hydropower value) of the environmental constraint by $Cost(c)$, and the benefit of this environmental policy by $B(c)$. An

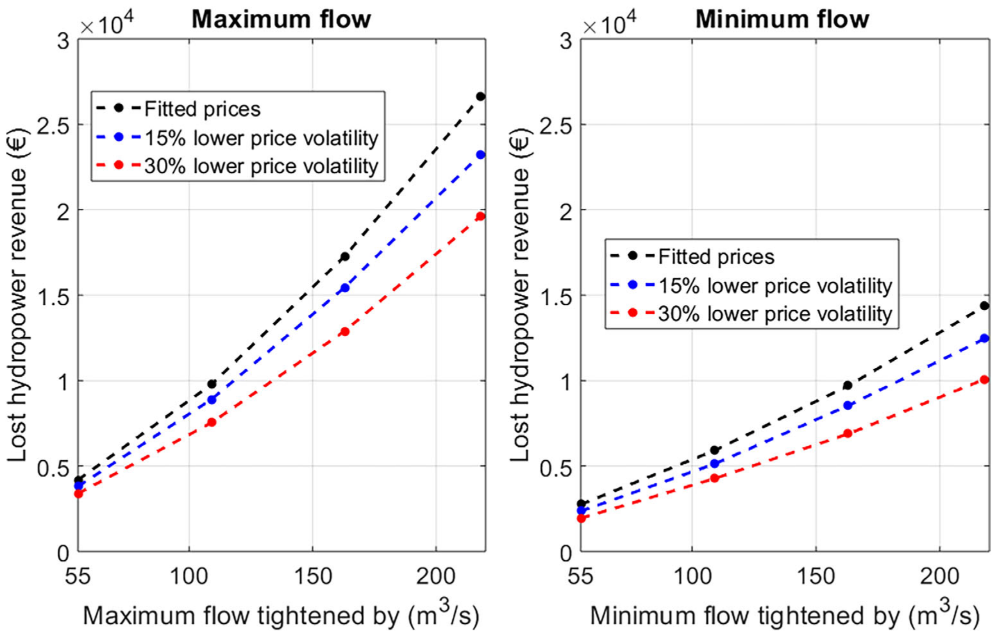

FIGURE 6 Decrease in hydropower value related to tightened maximum (left) and minimum (right) flow constraints [Color figure can be viewed at wileyonlinelibrary.com]

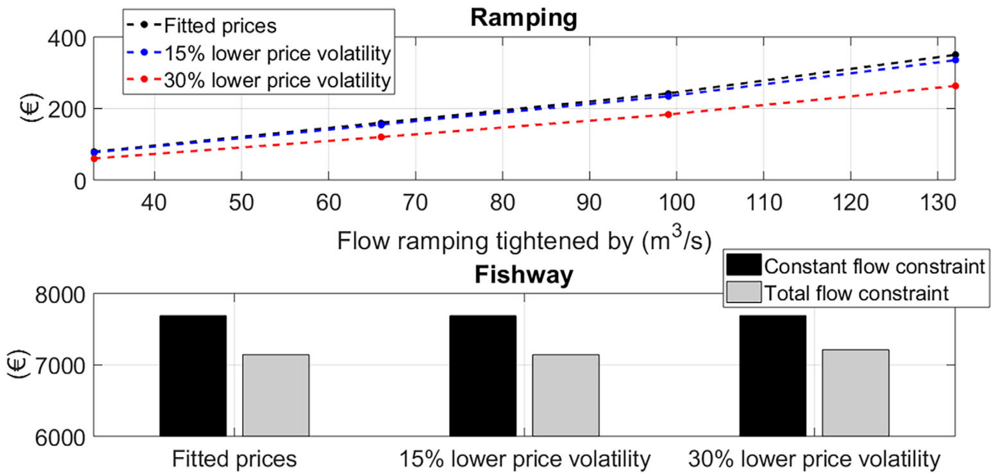

FIGURE 7 Decrease in hydropower value related to tightened flow ramping (top) constraints and fishway flow requirements (down) [Color figure can be viewed at wileyonlinelibrary.com]

optimally set constraint maximizes the net benefit of the policy: $B(c) - Cost(c)$. Therefore, the optimal policy c^* equalizes the marginal costs (mc) with the marginal benefits (mb):

$$mb(c^*) = \frac{dB(c^*)}{dc^*} = \frac{dCost(c^*)}{dc^*} = mc(c^*). \tag{19}$$

Figure 6 shows that the economic cost of tightened hydropower flow level constraints $c \in \{minimum\ flow, maximum\ flow\}$ is convex:

$$\frac{dCost(c)}{dc} = mc(c) > 0; \frac{d^2Cost(c)}{dc^2} = \frac{d}{dc}mc(c) > 0. \tag{20}$$

The optimal minimum flow policy when electricity price volatility decreases is illustrated in Figure 8. The marginal economic cost increases as a function of minimum flow (dotted black, blue, and red). We assume that the marginal benefit of tighter environmental constraints is decreasing (solid grey). This assumption is realistic when tightening the constraint initially provides large benefits for the river

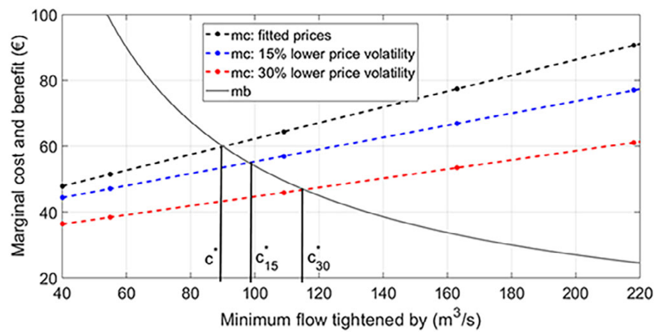

FIGURE 8 Marginal cost and benefit related to tightened minimum flow constraint [Color figure can be viewed at wileyonlinelibrary.com]

ecosystem and recreation but later provides diminishing benefits. The optimal minimum flow with original prices is denoted by c^*. When the standard deviation of electricity prices decreases by 15%, the constraint should be tightened to c^*_{15}. When the standard deviation of electricity prices decreases further by 30%, the constraint should be tightened to c^*_{30}.

Setting the optimal environmental flow constraint level presented in Figure 8 requires information about the costs and benefits of the environmental flow regulation in rivers, both of which are hard to quantify. Due to the asymmetry of information between the hydropower operator and the environmental regulator, the actual cost of the flow constraints (the lost hydropower revenue) should be approximated through hydropower operation simulations or statistical analysis of the electricity market and hydropower generation data. The benefits related to environmental regulation cannot be quantified precisely, but should be evaluated using empirical valuation techniques. Consequently, the optimal environmental constraint principle $mb(c^*) = mc(c^*)$ can be thought of as a general guideline for optimal environmental flow regulation, not as a fully quantifiable optimality condition.

6 | DISCUSSION AND CONCLUSION

This article examines the cost of environmental restrictions on a hydropower plant under varying electricity market conditions. Hydroelectric power plants can adjust quickly to the changes in the electricity market due to its properties of flexibility and storage. Their importance is highlighted even more as we move towards a more renewables dominated electricity systems with high intermittencies, such as wind and solar. Solutions to variability are being searched for both in the supply and demand side of electricity markets. Technological advancements, greater electrification of society, and attitudinal changes can enable higher flexibility on the demand side that will complement hydropower as a flexible source of electricity generation. Our driving hypothesis in this article is that if higher demand response capacity helps to smooth out the variation in power markets and electricity price volatility decreases, then that has implications on setting environmental restrictions on hydropower generation.

Our main finding is that the economic cost of environmental flow constraints decreases with lower price volatility. Environmental flows are increasingly highlighted in riverine management and are important tool for ensuring sufficient water volumes in various cases, especially related to management of fisheries and ecosystems in regulated river systems (Tharme, 2003). However, even though benefits of environmental flows are clear, discussion is still continuing on the economic costs of the constrains. Thus, a wider economical perspective including electricity market influence is needed. The optimal environmental constraint level should set such that the marginal cost equals the marginal benefit. In this framework, which acknowledge also variation in electrical market demand, supply and electricity prices, we illustrate that the optimal environmental flow restriction should be tightened if price volatility decreases. In practice, this means that the environmental regulator should be informed about the electricity markets and their influence on actual cost of the environmental flow release.

Prices signal the temporal value of electricity in power markets, and lower price volatility signals a lower value for flexibility in the margin. From ecosystem and fisheries point of view, this means improved cost estimations of real costs arriving from the environmental constrains, and thus help to target and find balance from ecological and economical needs. Traditionally, environmental flow constrains have been set up using mainly fisheries, ecosystem, and recreational targets (Chen & Olden, 2017). Our results indicate that also price volarity could be taken account in the assessment. Especially, modelling hydropower operation both with the hourly and on the intra-hour electricity markets would improve the value estimation of hydropower as a balancing resource. Additionally, hydrodynamic modelling and environmental valuation methods for evaluating the effect of hydropeaking on aquatic habitat composition and recreational value in river systems are required for a site-specific cost–benefit analysis of hydropower environmental flow regulation.

Fishways are tools for improving environmental fragmentation of regulated river systems and improving ecological connectivity in river systems (Williams et al., 2012). Well-functioning fishways need sufficient water volumes especially for attractant flow conditions. One of the main management questions has been the cost of the released water to the fishways, and its influence on hydropower production. In this study, we also examined the effect of a fishway flow requirement on the value of hydropower generation. We showed that if the hydropower operator can optimize the fishway flow allocation, then the loss in hydropower value is lower than under the constant fishway flow scenario. This is because the fishway flow can be adjusted such that the turbine flow ramping constraint is slacked, which enables higher hydropower turbine flow flexibility. Our results thus suggest that if a well-functioning fishway tolerates some flow variation, then the cost of the fishway becomes less expensive for the hydropower plant. In next steps, more intensive analysis combining the needs for various fishway and passage types and river systems should be analysed, and thus providing more detailed information for environmental managers. However, our results already show clearly that electrical market demands could be beneficial to consider also in environmental permits, especially if fishery and ecological demands tolerate the variation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Hannu Huuki https://orcid.org/0000-0003-1202-1100
Ali Torabi Haghighi https://orcid.org/0000-0002-5157-0156
Hannu Marttila https://orcid.org/0000-0002-9744-2483

ENDNOTE

[1] The high inflow season from May to August can be seen as a separate flow regime with a restricted short-term flow regulation potential.

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APPENDIX A: LAGRANGIAN FUNCTION AND THE KUHN-TUCKER CONDITIONS

The Lagrangian function for the constrained optimization problem presented in Equations (1)–(7) is:

$$\mathcal{L}=\sum_{t=1}^{T}(p_t q(h_t))-\lambda\left(\sum_{t=1}^{T}(h_t+f_t)-R\right)-\mu\left(-\sum_{t=1}^{T}f_t+F\right)$$

$$-\sum_{t=1}^{T}\rho_t(-h_t)-\sum_{t=1}^{T}\zeta_t(h_t-\overline{h})-\sum_{t=1}^{T}\kappa_t(\underline{f}-f_t)$$

$$-\sum_{t=1}^{T}\tau_t(\underline{flow}-(h_t+f_t))-\sum_{t=1}^{T}\sigma_t(h_t+f_t-\overline{flow})$$

$$-\sum_{t=2}^{T}\alpha_t(\underline{r}-(h_t+f_t-h_{t-1}-f_{t-1}))-\sum_{t=2}^{T}\beta_t(h_t+f_t-h_{t-1}-f_{t-1}-\overline{r}). \quad (A1)$$

The Kuhn-Tucker conditions are:

$$\frac{\partial\mathcal{L}}{\partial h_t}=\mathcal{L}_h=p_t q'(h_t)-\lambda+\rho_t-\zeta_t+\tau_t-\sigma_t=0, t=1 \quad (A2)$$

$$\frac{\partial\mathcal{L}}{\partial f_t}=\mathcal{L}_f=-\lambda+\mu+\kappa_t+\tau_t-\sigma_t=0, t=1 \quad (A3)$$

$$\frac{\partial\mathcal{L}}{\partial h_t}=\mathcal{L}_h=p_t q'(h_t)-\lambda+\rho_t-\zeta_t+\tau_t-\sigma_t+\alpha_t-\alpha_{t+1}-\beta_t+\beta_{t+1}=0, t=2,\ldots T \quad (A4)$$

$$\frac{\partial\mathcal{L}}{\partial f_t}=\mathcal{L}_f=-\lambda+\mu+\kappa_t+\tau_t-\sigma_t+\alpha_t-\alpha_{t+1}-\beta_t+\beta_{t+1}=0, t=2,\ldots T \quad (A5)$$

$$\frac{\partial\mathcal{L}}{\partial\lambda}=R-\sum_{t=1}^{T}(h_t+f_t)\geq 0, \lambda\geq 0, \lambda\frac{\partial\mathcal{L}}{\partial\lambda}=0 \quad (A6)$$

$$\frac{\partial\mathcal{L}}{\partial\mu}=\sum_{t=1}^{T}f_t-F\geq 0, \mu\geq 0, \mu\frac{\partial\mathcal{L}}{\partial\mu}=0 \quad (A7)$$

$$\frac{\partial\mathcal{L}}{\partial\rho_t}=h_t\geq 0, \rho_t\geq 0, \rho_t\frac{\partial\mathcal{L}}{\partial\rho_t}=0, t=1,\ldots T \quad (A8)$$

$$\frac{\partial\mathcal{L}}{\partial\zeta_t}=-h_t+\overline{h}\geq 0, \zeta_t\geq 0, \zeta_t\frac{\partial\mathcal{L}}{\partial\zeta_t}=0, t=1,\ldots T \quad (A9)$$

$$\frac{\partial\mathcal{L}}{\partial\kappa_t}=-\underline{f}+f_t\geq 0, \kappa_t\geq 0, \kappa_t\frac{\partial\mathcal{L}}{\partial\kappa_t}=0, t=1,\ldots T \quad (A10)$$

$$\frac{\partial\mathcal{L}}{\partial\tau_t}=h_t+f_t-\underline{flow}\geq 0, \tau_t\geq 0, \tau_t\frac{\partial\mathcal{L}}{\partial\tau_t}=0, t=1,\ldots T \quad (A11)$$

$$\frac{\partial\mathcal{L}}{\partial\sigma_t}=-h_t-f_t+\overline{flow}\geq 0, \sigma_t\geq 0, \sigma_t\frac{\partial\mathcal{L}}{\partial\sigma_t}=0, t=1,\ldots T \quad (A12)$$

$$\frac{\partial\mathcal{L}}{\partial\alpha_t}=h_t+f_t-h_{t-1}-f_{t-1}-\underline{r}\geq 0, \alpha_t\geq 0, \alpha_t\frac{\partial\mathcal{L}}{\partial\alpha_t}=0, t=2,\ldots T \quad (A13)$$

$$\frac{\partial\mathcal{L}}{\partial\beta_t}=h_{t-1}+f_{t-1}-h_t-f_t+\overline{r}\geq 0, \beta_t\geq 0, \beta_t\frac{\partial\mathcal{L}}{\partial\beta_t}=0, t=2,\ldots T \quad (A14)$$

The multiplier λ expresses the shadow price of the reservoir. It shows how the value of the optimized target function (sum of hourly profits) changes when the total flow constraint in Equation (2) (see text) is relaxed by one unit (total reservoir R is increased marginally).

The multiplier μ expresses the shadow price of the total fishway flow requirement. It shows how the value of the optimized target function changes when the total fishway flow constraint in Equation (4) (see text) is relaxed by one unit (total fishway flow requirement $-F$ is increased marginally, that is, less flow required through the turbine passing channel).

APPENDIX B: HYDROPOWER OPERATION CONSTRAINTS IN TWO-PERIOD FRAMEWORK

The model horizon is two periods: $t = 1,2$. It is assumed that the electricity price in the first period is higher than in the second period: $p_1 > p_2$. The price difference is marked by $\Delta p > 0$. Consequently, a revenue maximizing hydropower plant aims to allocate as much flow through turbines as possible during the first period.

B.1. | Maximum and minimum flow restrictions

The hydropower operator maximizes the total revenue

$$\max_{h_t} \sum_{t=1}^{2} p_t q(h_t) \tag{B1}$$

subject to the operation constraints

$$\sum_{t=1}^{2} h_t = R, \tag{B2}$$

and

$$\underline{flow} \le h_t \le \overline{flow}, t = 1, 2. \tag{B3}$$

The Lagrangian is the following:

$$\mathcal{L} = \sum_{t=1}^{2} p_t q(h_t) - \lambda \left(\sum_{t=1}^{2} h_t - R \right) - \sum_{t=1}^{2} \tau_t \left(\underline{flow} - h_t \right) - \sum_{t=1}^{2} \sigma_t \left(h_t - \overline{flow} \right).$$

Assume that the maximum flow constraint in period 1 binds: $\sigma_1 > 0$. The first-order conditions with respect to turbine flow in periods 1 and 2 can be written as:

$$\frac{\partial \mathcal{L}}{\partial h_1} = p_1 q' - \lambda - \sigma_1 = 0, \tag{B5}$$

$$\frac{\partial \mathcal{L}}{\partial h_2} = p_2 q' - \lambda = 0. \tag{B6}$$

The shadow cost of maximum flow constraint can be derived from Equations (B5) and (B6) as:

$$\sigma_1 = (p_1 - p_2) q' = \Delta p q'. \tag{B7}$$

If the price difference decreases $\Delta p^r < \Delta p$, the cost of the maximum flow restriction decreases:

$$\sigma_1^r = \Delta p^r q' < \Delta p q' = \sigma_1. \tag{B8}$$

Next, instead of the maximum flow constraint binding, assume that the minimum flow constraint binds in the second period: $\tau_2 > 0$. The first-order conditions with respect to the turbine flow in periods 1 and 2 can be written as:

$$\frac{\partial \mathcal{L}}{\partial h_1} = p_1 q' - \lambda = 0, \tag{B9}$$

$$\frac{\partial \mathcal{L}}{\partial h_2} = p_2 q' - \lambda + \tau_2 = 0. \tag{B10}$$

The shadow cost of the minimum flow constraint can be derived from Equation (B.9) and Equation (B.10) as:

$$\tau_2 = (p_1 - p_2) q' = \Delta p q'. \tag{B11}$$

B.2. | Flow ramping restriction

The hydropower operator maximizes the total revenue

$$\max_{h_t} \sum_{t=1}^{2} p_t q(h_t) \tag{B12}$$

subject to the operation constraints

$$\sum_{t=1}^{2} h_t = R, \tag{B13}$$

and

$$\underline{r} \le h_2 - h_1 \le \bar{r}. \tag{B14}$$

The Lagrangian is the following:

$$\mathcal{L} = \sum_{t=1}^{2} p_t q(h_t) - \lambda \left(\sum_{t=1}^{2} h_t - R \right) - \alpha_2 (\underline{r} - (h_2 - h_1)) - \beta_2 (h_2 - h_1 - \bar{r}). \tag{B15}$$

Assume that the down flow ramping constraint binds: $\alpha_2 > 0$. The first-order conditions with respect to the turbine flow in periods 1 and 2 can be written as:

$$\frac{\partial \mathcal{L}}{\partial h_1} = p_1 q' - \lambda - \alpha_2 = 0, \tag{B16}$$

$$\frac{\partial \mathcal{L}}{\partial h_2} = p_2 q' - \lambda + \alpha_2 = 0. \tag{B17}$$

The shadow cost of the flow ramping constraint can be derived from Equations (B16) and (B17) as:

$$\alpha_2 = \frac{1}{2} (p_1 - p_2) q'. \tag{B18}$$

If the price difference decreases $\Delta p^r < \Delta p$, the cost of the flow ramping restriction decreases:

$$\alpha_2^r = \frac{1}{2}\Delta p^r q' < \frac{1}{2}\Delta p q' = \alpha_2. \tag{B19}$$

B.3. | Total fishway flow requirement

The hydropower operator maximizes the total revenue

$$\max_{h_t, f_t} \sum_{t=1}^{2} p_t q(h_t) \tag{B20}$$

subject to the operation constraints

$$\sum_{t=1}^{2} (h_t + f_t) = R, \tag{B21}$$

$$F = \sum_{t=1}^{2} f_t, \tag{B22}$$

$$\underline{f} \le f_t, t = 1, 2, \tag{B23}$$

$$\underline{flow} \le h_t + f_t \le \overline{flow}, t = 1, 2, \tag{B24}$$

$$\underline{r} \le h_2 + f_2 - h_1 - f_1 \le \bar{r}, \tag{B25}$$

The Lagrangian is the following:

$$\mathcal{L} = \sum_{t=1}^{2} p_t q(h_t) - \lambda\left(\sum_{t=1}^{2}(h_t + f_t) - R\right) - \mu\left(F - \sum_{t=1}^{2} f_t\right)$$

$$-\sum_{t=1}^{2} \kappa_t (\underline{f} - f_t) - \sum_{t=1}^{2} \tau_t (\underline{flow} - (h_t + f_t)) - \sum_{t=1}^{2} \sigma_t (h_t + f_t - \overline{flow})$$

$$-\alpha_2(\underline{r} - (h_2 + f_2 - h_1 - f_1)) - \beta_2(h_2 + f_2 - h_1 - f_1 - \bar{r}). \tag{B26}$$

Assume that the total fishway flow constraint is tighter than the minimum fishway flow constraint set for each hour: $F > 2\underline{f}$. This implies that the minimum fishway flow constraint $\underline{f}$ applies only in the first ($\kappa_1 > 0$), the second ($\kappa_2 > 0$) or in neither of the periods ($\kappa_1 = \kappa_2 = 0$).

We derive two separate results. First, assume that the maximum flow restriction binds in the first period: $\sigma_1 > 0$. The first-order conditions with respect to turbine flow h_t and fishway flow f_t in periods 1 and 2 can then be written as:

$$\frac{\partial \mathcal{L}}{\partial h_1} = p_1 q' - \lambda - \sigma_1 = 0 \tag{B27}$$

$$\frac{\partial \mathcal{L}}{\partial f_1} = -\lambda + \mu - \sigma_1 + \kappa_1 = 0 \tag{B28}$$

$$\frac{\partial \mathcal{L}}{\partial h_2} = p_2 q' - \lambda = 0 \tag{B29}$$

$$\frac{\partial \mathcal{L}}{\partial f_2} = -\lambda + \mu = 0 \tag{B30}$$

The shadow cost of the minimum environmental flow constraint can be derived from Equations (B27)–(B30) as:

$$\kappa_1 = (p_1 - p_2)q', \tag{B31}$$

and the shadow cost of the total environmental flow requirement can be derived from (B30) as:

$$\mu = \lambda. \tag{B32}$$

Secondly, assume that the down ramp restriction binds: $\alpha_2 > 0$. The first-order conditions with respect to the turbine and fishway flows in periods 1 and 2 can be written as:

$$\frac{\partial \mathcal{L}}{\partial h_1} = p_1 q' - \lambda - \alpha_2 = 0, \tag{B33}$$

$$\frac{\partial \mathcal{L}}{\partial f_1} = -\lambda + \mu - \alpha_2 + \kappa_1 = 0, \tag{B34}$$

$$\frac{\partial \mathcal{L}}{\partial h_2} = p_2 q' - \lambda + \alpha_2 = 0, \tag{B35}$$

$$\frac{\partial \mathcal{L}}{\partial f_2} = -\lambda + \mu + \alpha_2 = 0. \tag{B36}$$

The shadow cost of the minimum flow ramp condition can be derived from (B33) and (B35) as:

$$\alpha_2 = \frac{1}{2}(p_1 - p_2)q' > 0. \tag{B37}$$

The shadow cost of the total fishway flow requirement can be derived from (B35) as:

$$\mu = \lambda - \alpha_2 < \lambda. \tag{B38}$$