Hydropeaking Mitigation with Re-Regulation Reservoirs

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Abstract

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Abstract

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Introduction

Hydropower is one of the largest renewable electricity sources in the European Union (EU), accounting for 36% of renewable electricity and 10% of gross electricity production as of 2018 (Alsaleh et al., 2023). These figures are expected to grow as the European Commission has proposed a European Green Deal to make Europe climate-neutral by 2050. As a result, with hydropower being a flexible power source, its role in balancing and stabilizing the power market will grow (Ashraf et al., 2018). However, hydropower's flexibility causes sudden variations in sub-daily flows in rivers, i.e., hydropeaking, defined as an artificial river flow regime caused by the cyclical release of water. This is due to the rapid switching between increasing and decreasing power generation in hydropower plants (HPP), in response to the power market fluctuations (Bieri et al., 2014). Manipulating the power demand may indirectly alter flow conditions and intensify hydropeaking regimes in rivers (Ashraf et al., 2022). In turn, artificial flow fluctuations induced by human activities are considered a primary threat to aquatic ecology (Bunn et al., 2002). Altering natural flow conditions can result in ecological stresses as they are widely recognized as significant drivers of ecological sustainability of rivers along with their associated floodplains (Poff et al., 1997).

Hydropeaking leads to a high flow pattern variability significantly impacting river ecosystems (Meile et al., 2011). On a temporal scale, variations in flow patterns driven by hydropeaking are significantly more prominent than other forms of flow variations, such as seasonal flow changes or daily flow fluctuations (Bejarano et al., 2018). Furthermore, the magnitude of hydropeaking releases can be much larger than those of natural flows, leading to significant changes in water depth and velocity (Shen et al., 2010). Aiming at mitigating the adverse impacts of hydropeaking, governing authorities usually impose environmental constraints on HPPs operations, such as setting minimum environmental flows and limits on flow change rates. It has been demonstrated that implementing such environmental constraints can effectively mitigate sub-daily flow fluctuations (Olivares et al., 2021). However, these constraints will result in economic losses for HPPs (Pérez-Díaz et al., 2010; Guisández et al., 2016). Alternatively, the introduction of a re-regulation reservoir (RRR) can mitigate the loss of operational flexibility caused by environmental constraints. This strategic measure enhances the plant's operational flexibility while simultaneously mitigating economic losses arising from operational constraints (Pérez-Díaz et al., 2010).

Bieri et al. (2014) conducted a study on RRRs in the upper Aare River basin, Switzerland, focusing on mitigating rapid flow changes, specifically ramping rates, rather than altering peak discharge or off-peak discharge. The study examined four RRR volumes (50,000; 60,000; 80,000; 100,000 m^3) and demonstrated significant reductions in flow ramping rates compared to existing values or future projected rates. Similarly, Tonnolla et al. (2017) utilized ecological indicators to evaluate the same retention volumes at the Innertkirchen HPP. The results revealed that volumes of 80,000 $m^3$and 100,000 m^3 led to the most significant ecological improvement. On the other hand, Anindito et al. (2019) studied the cost-effectiveness of re-regulation reservoirs (RRRs) in addressing ecological impacts from sub-daily hydropeaking. They evaluated the techno-economic performance of a 360,000 m^3 RRR to mitigate hydrological alterations caused by HPPs. The study explored different investment costs for RRR and provided comprehensive recommendations for profitability. Popa et al. (2019) conducted a qualitative analysis on the feasibility of constructing a RRR downstream of the Golesti HPP. The study aimed to release water, with or without smoothed fluctuations, through a small HPP to generate green electricity, while minimizing adverse effects on the riverbed and downstream ecosystem. However, the study did not address ecological and hydrological concerns associated with this approach. Olivares et al. (2021) assessed the impact of small RRRs situated downstream of HPPs, with a focus on the tradeoffs between flow flashiness (ramp rate) and power system costs. Using a system-wide cost-minimization model, the study revealed that small RRRs successfully mitigate ramping rates while minimizing the cost increase caused by operational constraints. In a recent study, Reindl et al. (2023) examined on a hydropeaking diversion HPP at the Swiss/Austrian border. The analysis supported the use of a reservoir with a volume of 300,000 m^3, which was deemed optimal for the site. Larger retention basins (>1,000,000 m^3) theoretically could provide superior effects, but land availability constraints rendered their construction infeasible (Reindl et al., 2023). Most of the prior research has predominantly examined RRRs from ecological or economic perspectives for specific localities. Studies incorporating hydrological aspects often centered on ramping rates (flow flashiness, rate of flow change, etc.) neglecting the consideration of flow magnitude and were limited by land availability (RRR volume) or economic constraints. In contrast, our study exclusively concentrates on the theoretical design of RRRs from a hydrological standpoint, encompassing both flow magnitude and ramping rates as essential factors for analysis. The objectives of this study are to; 1) Design a model to determine the required volume of the RRR to shave the peak flow, increase minimum flow, and limit ramping rates. 2) Examine the potential of deploying RRR downstream of HPPs by utilizing the model developed in this study; 3) Validate the model and optimize its applicability towards a re-regulation strategy for RRR operation. To the best of our knowledge, this is the first study that attempts to develop a model exclusively focused on the design of RRRs from a hydrological standpoint.

Materials and Methods

To address the key research objectives of this study, a mixed type of methodological approach was employed. The first and second parts consist of a desk review of published literature in peer reviewed journals, periodicals, proceedings, and book chapters on the concept of RRRs with a snapshot of main mechanisms involved in their operation. The desk review also covered policies, regulations, and standards of ecological criteria of RRR operation. The third part provides a comprehensive description of the development of a model-based design of RRRs.

Re-regulation Reservoir (RRR) Conceptual Approach

A RRR stores a portion or the entirety of excess flow of a river regime and releases it back at an adequate rate to smooth out any sub-daily alterations in the regime (Figure 1). Figure 1.a. is a schematic that visually illustrates the operation of the RRR. The main idea of the RRR is to restore the regulated river regime back as much as possible to its natural regime. This could be achieved by storing the excess flow (red phase in Fig. 1) from the HPP during up-ramping events (i.e., starting or increasing the turbine power production), to be released later during down-ramping events, i.e., stopping or decreasing the turbine power production (blue phase, Fig. 1), through two automated gates that regulate the flow into and out of the reservoir. These gates are controlled by a re-regulation algorithm developed in this study, which determines the appropriate timing to open the inlet and outlet gates. Under ideal circumstances, a RRR can potentially fully restore a river regime to its natural state and ensure a continuous minimum flow to accommodate ecological requirements of watercourses. However, this might require a large RRR volume which might not always be feasible due to economic or land availability constraints. As such, when the RRR volume is limited, it should be operated to achieve the priority objectives and then fulfill the secondary objectives whenever possible. A simplified hydrograph of a natural river regime versus a regulated river regime at a sub-daily scale is displayed in Figure 1.b. The hydrograph demonstrates excess water occurrence that could be stored in RRRs (i.e., red), and potential flow release back into the river (i.e., blue).

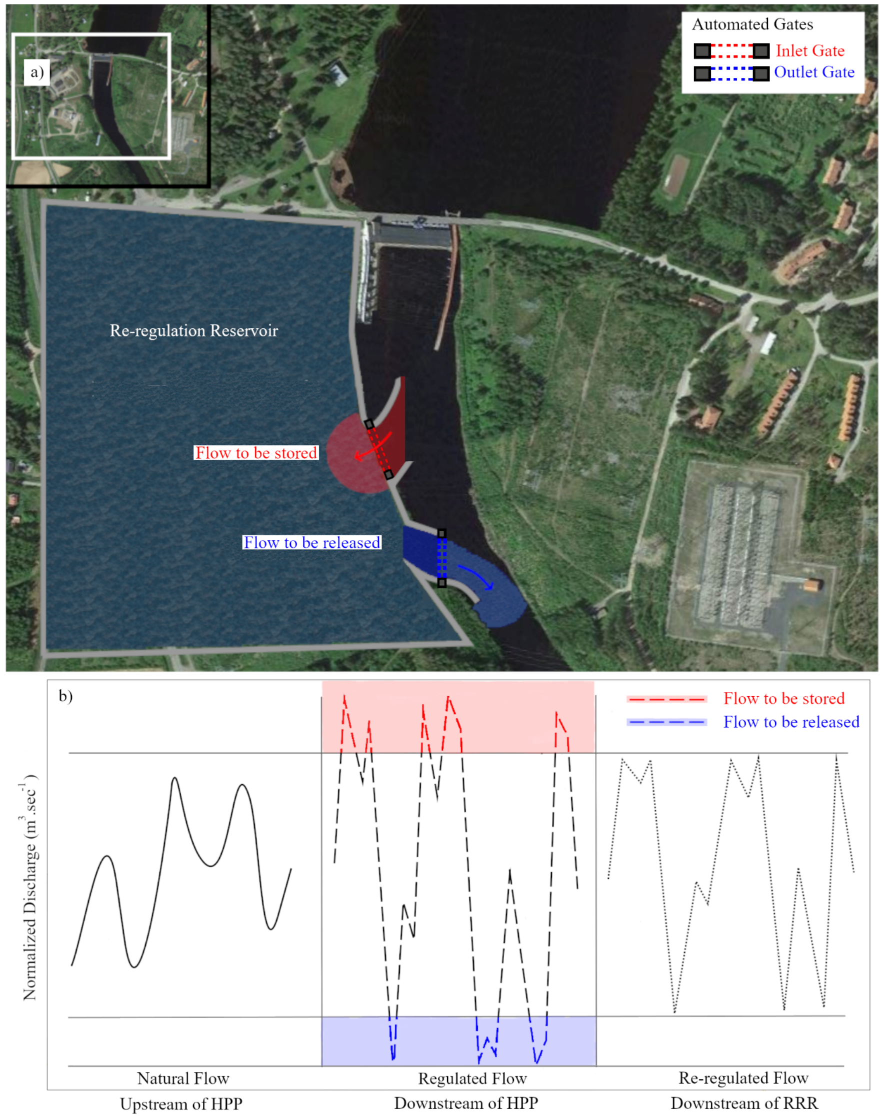

Figure 1. A conceptual approach to RRR operation illustrating a peak flow of a river i.e., red phase that can be potentially stored by RRR and a corresponding regulated flow release back into the river i.e., bule phase. a) illustrates a hypothetical image of RRR and a river; b) presents a conceptual hydrograph of the river flow starting from upstream of the HPP and progressing downstream of RRR. Google Earth 9.185, (2020) Petäjäskoski, 66° 16’ 10” N, 25° 20’ 17” E elevation 49m. [Online] Available at: https://earth.google.com [Accessed 5 March 2023].

Hydrological and Ecological Criteria for Hydropeaking Mitigation

The hydrologic alteration in a river can be governed on spatial and temporal scales through a change in magnitude, rate of flow change, frequency, and duration of flow. Any deviation from the natural states of these parameters is associated with a discrete environmental impact (Haghighi et al., 2014). Thus, to minimize the impact, variations in these parameters should be restricted to thresholds. However, despite extensive research on hydropeaking, only a few European countries (i.e., Switzerland and Austria) have national regulations defining hydropeaking thresholds (Moreira et al., 2019). While current literature mainly focuses on qualitative targets, setting thresholds and targets for the aforementioned factors is still considered a challenge. There is still a lack of consensus to specify thresholds for the mentioned parameters (Costa et al., 2017).

The main adverse impact of down ramping is fish stranding and changes in habitat locations, which results in major ecological pressure on the river (Nagrodski et al., 2012). Besides down ramping rates, minimum flow and peak flow magnitudes affecting spawning and intra-gravel life stages are also important factors to consider (Moreira et al., 2019). Up ramping rate presents one additional factor that can cause fish drift and impact the ecological conditions. In terms of water uses, flow fluctuations caused by hydropeaking can be intense and disruptive for existing irrigation schemes (Bieri et al, 2016) and negatively impact recreational activities such as fishing, kayaking, and swimming (Charmasson et al., 2011). Finally, hydropeaking can worsen the drinking water quality by stirring up sediments and other pollutants. Therefore, in this study, we will focus on how RRRs can contribute to flow management, including ramping rates, minimum flow, and peak flow which are critical criteria for hydropeaking mitigation (Moreira et al., 2019 & Richter et al., 2010).

Model-based Design Development

A full restoration of a river regime to its natural state requires a large RRR volume which might not always be feasible due to economic or land availability constraints. However, shaving the peak flow, increasing the minimum flow, and limiting ramp rates can substantially restore the river regime to its natural state. Such objectives could be resolved with RRRs which necessitate flows to be retained and adequately released into the waterway (Fig.1). Inadequate (i.e., too slow) water release might result in small volume availability in the RRR to accommodate water from peak flows and up-ramping events. Thus, to effectively manage RRRs, a model is required to determine the timing and amount of water that needs to be stored or released. Once this is achieved, the model can calculate the required RRR volume. With this mind, the theoretical foundation of the model developed in this study was based on two main objectives. The primary objective of the RRR is to reduce the hourly peak flow (Q_{max}) and increase the minimum hourly flow (Q_{min}) induced by hydropeaking. Secondarily, the RRR aims to reduce the up- and down- ramping rates and increase the timespan during flow change occurs. The ramping flow rate ([?]Q(t)) [$m^3s^{-1}min^{-1}$] given in equation (Eq. 1), represents the increase (i.e., up ramping, positive values) or decrease (down ramping, negative values) in the flow over a given time step, where, Q(t) is the discharge at time t ($m^3.s^{-1}$), Q(t - [?]t) is the discharge at time t- [?]t ($m^3.s^{-1}$) and [?]t is the time step (min).

$Q\left(t\right) = \frac{Q(t) - Q(t-t)}{t}$ (Eq. 1)

A flow pattern resembling a regulated river regime exposed to frequent hydropeaking was needed to design the model. For this purpose, Kemijoki River, one of the most regulated rivers in Finland, with a mean annual discharge of 515 m^3s^{-1} (Ashraf et al., 2016) was selected and hourly discharge data for the lower part of the main river channel of the Taivalkoski HPP from 2015 to 2017 was obtained from national datasets maintained by the Finnish Environment Institute (Hertta-database, for more details, see Ashraf et al., 2016). To generate the required flow pattern (hereinafter called scaled flow), characterized by an average discharge of 1 $m^3.s^{-1}$, the Taivalkoski HPP discharge data was scaled down by dividing the hourly discharge by the average hourly discharge per day (Eq. 2).

$Q_{\text{scaled}}\ \left(t\right) = \frac{Q(t)}{Q_{\text{avg}}(d)}$(Eq. 2)

Where Q_{scaled} (t) is the scaled discharge at time t ($m^3.s^{-1}$), Q (t) is the actual discharge at time t ($m^3.s^{-1}$), and Q_{avg} (d) is the average hourly discharge per day ($m^3.s^{-1}$).

Once the scaled flow is attained, it is possible to establish a hierarchy of operational objectives with a range of distinct thresholds that dictate the timing and amount of water that needs to be stored or released by the RRR. Thus, a re-regulation algorithm that operates the RRR based on the following list of hierarchal objectives and their associated thresholds was developed;

- Priority 1, Reliability and Safety: the inflow and outflow discharges would not lead to the overflow or the depletion of the re-regulation basin in the next time step.

- Priority 2, Peak and Minimum flows: the operation of the re-regulation basin would reduce the peak flow and increase the minimum flow by 10 to 50% (hereinafter referred to as flow adjustment). Thus, the peak flow is limited between 50 and 90%xQmax and the minimum flow between 110 and 150%xQmin.
- Priority 3, Maximum Up- and Down-ramping rates: up-ramping rates are limited to a distinct threshold when the flow is greater than the average daily flow. Down-ramping rates are limited to a distinct threshold when the flow is smaller than the average daily flow. The investigated thresholds for up and down ramping rates (r.r) are 1, 1.5, 2, 2.5, 3, 3.5, 4, and -1, -1.5, -2, -2.5, -3, -3.5, -4 $m^3sec^{-1}min^{-1}$, respectively. To include these r.r thresholds in the scaled flow re-regulation algorithm, they had to be scaled down according to equation (Eq. 3)r. $r_{scaled} = \frac{r.r}{Qavg(a)}$ (Eq. 3) Where r.r $_{scaled}$ is the scaled r.r threshold ($m^3sec^{-1}min^{-1}$), r.r is the unscaled r.r threshold, and $Q_{avg}(a)$ is the annual average discharge (m^3sec^{-1}).
- Priority 4, Optimal flow: A flow is restored to a daily average flow whenever possible.
- Priority 5, Optimal up and down ramping rates: Whenever possible, the ramping rate thresholds are satisfied regardless if the flow is greater or smaller than the average daily flow.

As the ideal flow conditions for the various ecosystem services may be different, a range of thresholds was utilized in the algorithm to determine the required RRR volume for several hydropeaking mitigation scenarios. Thus, the threshold range for flow magnitude was selected to include all the possible mitigation scenarios, by using 10% flow adjustment increments. Whereas, the ramping rate thresholds were carefully chosen to include a range of scenarios, by incrementally adjusting the lower and upper limits of the range. The threshold range started from a threshold below the average ramping rate and was extended to reach up to 50% of the maximum ramping rate, using increments of 0.5 $m^3sec^{-1}min^{-1}$. The unscaled average up- and down- ramping rates downstream of Taivalkoski HPP during 2015 to 2017 were 1.5085 and -1.36 $m^3sec^{-1}min^{-1}$, respectively. As such, the lower limit for ramping rate threshold was set to 1 $m^3sec^{-1}min^{-1}$. Whereas the maximum unscaled ramping rate reached up to 8 $m^3sec^{-1}min^{-1}$, as such the upper limit for the ramping rate threshold range was set to 4 $m^3sec^{-1}min^{-1}$. To further expand the scope of possible mitigation scenarios, thirty-five permutations were created and tested by matching the peak and minimum flow thresholds (i.e., priority 2) with ramp rate thresholds (i.e., priority 3). Hereinafter, the permutations will be referred to as P (X%, Y), with X% being the percentage adjusted from Qmax and Qmin i.e., (100-X) %xQmax and (100+X) %xQmin, while Y is the ramp rate threshold i.e., (Y) for up-ramping and (-Y) for down-ramping. One example from the permutations is P (10%, 2.5) which matches the 10% flow adjustment (i.e., 90%*Qmax and 110%*Qmin threshold) with a ramp rate threshold of 2.5 $m^3s^{-1}min^{-1}$. Additionally, we demonstrate how the RRR would re-regulate the flow downstream of Taivalkoski (Kemijoki) for permutation P (40%, 2) by using the re-regulation algorithm.

This model was used to determine the required volume of RRRs downstream of HPPs operating at the Kemijoki River. It has the potential to be utilized in other rivers with similar flow patterns to achieve the above listed priorities. However, the range of thresholds employed by the re-regulation algorithm must be modified to best suit the flow pattern of the investigated river. It is important to note the model assumes the location of the RRR is immediately downstream of the HPP, thus not accounting for flow velocity or the time required for water to reach the RRR. The model also assumes ideal RRR conditions with no consideration of any water losses that might occur due to evaporation and seepage.

Results

Table 1. presents our calculations showing clear theoretical possibilities for regulating hydropeaking with RRRs. For example, assuming that the future flow is consistent with the scaled flow of the study period, the required RRR volumes (Table 1) are sufficient to ensure the hydropeaking thresholds are respected throughout the year. The results indicate that, for most of the tested permutations, the required volume of the RRRs increased as the thresholds for peak and minimum hourly flows and the ramping rates became more stringent. Nonetheless, for some permutations, this trend was not observed. One example is the required RRR volume for permutations P (10%, 3.5, volume: 0.256 million cubic meters (MCM)) and P

(10%, 4, volume: 0.368 MCM) are larger than the reservoir volume needed for permutations P (10%, 2.5, volume: 0.147) and P (10%, 3, volume: 0.143) which have more stringent ramp rate threshold. Furthermore, for permutation P (10%, 4), the required RRR volume (0.368 MCM) decreases slightly compared to P (20%, 4, volume: 0.262 MCM), which has more stringent peak and minimum flow thresholds. Our theoretical approach demonstrates the relationship between the required RRR volume, daily peak discharge, and ramp rate thresholds (Figure 2).

Furthermore, the required RRR volume was determined for each month separately, illustrated in Figure 3. The results indicate that for most of the investigated permutations except permutations with 50% flow adjustment, July and August require the largest reservoir volume to achieve the objectives and priorities stated in section 2.3. Whereas, for permutations with a 50% flow adjustment, January is the month that requires the largest reservoir volume. However, it is important to note that January and February are the months with largest volume requirement when the ramp rate thresholds exceed 2.5 $m^3.s^{-1}.min^{-1}$ for permutations with a 10% flow adjustment. Additionally, the RRR operation for P (40%, 2) for the scaled flow downstream of Taivalkoski (Kemijoki) is demonstrated in Figure 4. For all the permutations, the RRR limits peak and minimum hourly flows and ramp rates according to thresholds defined by the algorithm. Nevertheless, Figure 4.a. demonstrates that the RRR increases the minimum flow beyond the defined threshold in numerous time steps without violating other priorities. However, as illustrated in Figure 4.b., there are time steps where priority 2 takes precedence over priority 3, causing the ramp rates to surpass the defined threshold.

Table 1. The required re-regulation reservoir volumes (MCM) for different permutations (scaled flow from 2015 to 2017).

	Flow Adjustment (%)	Flow Adjustment (%)	Flow Adjustment (%)	Flow Adjustment (%)	Flow Adjustment (%)	Flow Adjustment (%)	Flow Adjustment (%)
	Up	Down	**10%**	**20%**	**30%**	**40%**	**50%**
Up & Down Ramp rate ($m^3.s^{-1}.min^{-1}$)	**1**	**-1**	0.453	0.818	1.558	2.583	3.572
	1.5	**-1.5**	0.362	0.757	1.514	2.555	3.556
	2	**-2**	0.260	0.675	1.448	2.504	3.526
	2.5	**-2.5**	0.147	0.573	1.359	2.434	3.483
	3	**-3**	0.143	0.444	1.241	2.338	3.418
	3.5	**-3.5**	0.256	0.303	1.116	2.232	3.344
	4	**-4**	0.368	0.262	0.982	2.120	3.262

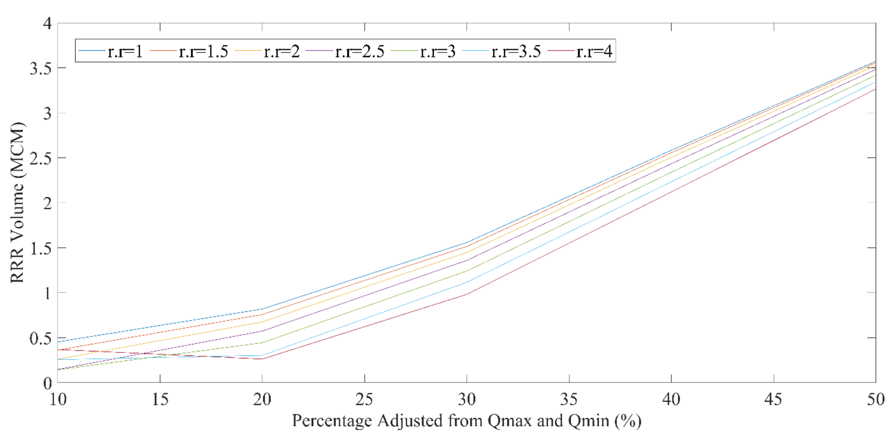

Figure 2. Required re-regulation reservoir volume for different flow and ramp rate thresholds (r.r is ramp rate).

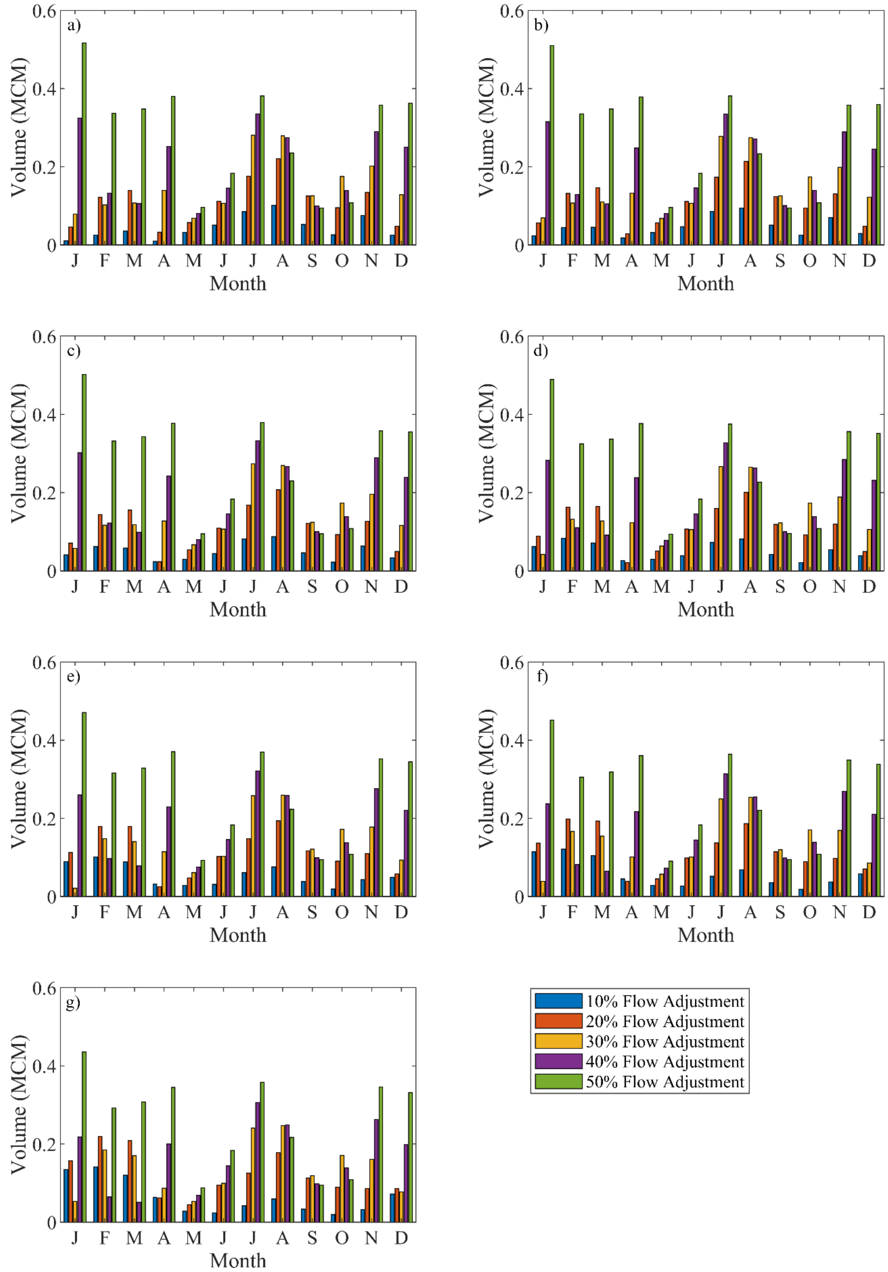

Figure 3. Required monthly volume of RRR for scaled flow, without carryover of stored water from one month to the other if there is any. The r.r for a) 1, b) 1.5, c) 2, d) 2.5, e) 3, f) 3.5, g) 4 $m^3s^{-1}min^{-1}$

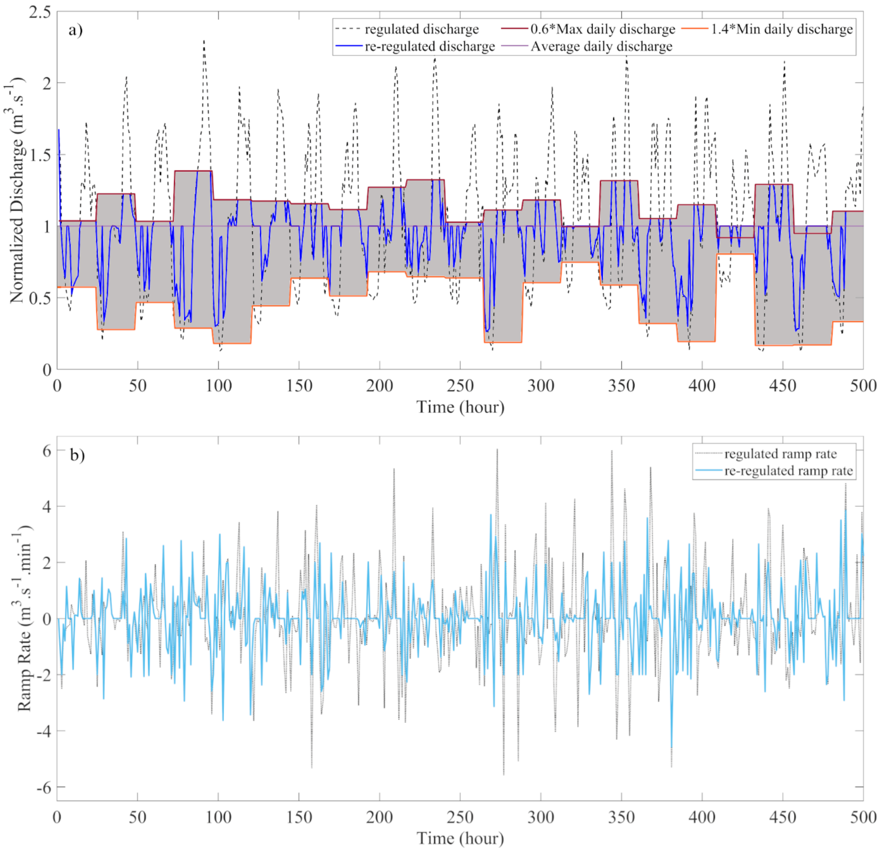

Figure 4. The performance of the re-regulation reservoirs to re-regulate the discharge for P (40%, 2) during 500 hours. (a) illustrates how the reservoir limits the discharge to the thresholds defined in the algorithm and achieves optimal conditions whenever possible. (b) distinctly shows the ramping rates before and after implementing the re-regulation reservoir.

Discussion

Re-regulation reservoirs (RRR) have emerged as a promising method for mitigating the ecological impacts of hydropeaking. While the efficacy of RRRs in mitigating hydropeaking impacts is still being assessed, early studies suggest that this novel approach may be a valuable tool for enhancing the ecological sustainability of hydropower operations. Studies have shown that RRRs can reduce the adverse impacts of hydropeaking downstream of hydropower plants and reduce the deleterious effects of hydropeaking on aquatic ecosystems (Tonolla et al., 2017). Compared to other mitigation measures, such as the installation of downstream flow control devices or modifying the operation of hydropower facilities, RRRs offer several advantages. These include greater flexibility and adaptability to changing environmental conditions, power, and water demand without increasing the operational cost of power systems. While RRRs also possess the potential to provide other services, such as water storage and flood control (Anindito et al., 2019; Premstaller et al., 2017; Tonolla et al., 2017). In practice, RRRs could be an artificial structure, natural water reservoir, flood plain or any other storage possibility near by the HPP. Our study did not prioritize the examination of structural or operational designs. Instead, we focused on exploring theoretical approaches to mitigate hydropeaking and developed a model to operate and estimate the required RRR volumes.

This study tested and determined the RRR volumes required to meet the objectives and priorities outlined in section 2.3 of the Kemijoki River downstream from Taivalkoski HPP using a re-regulation algorithm developed specifically for this study. The flow data of the Taivalkoski HPP was scaled down to create a base case that can be used for other similar HPPs. While we recognize that re-regulation is generally more manageable in smaller river systems due to their smaller reservoir capacities and volumes, our case data from a large river system can still be leveraged to explore theoretical possibilities for re-regulation practices. The results indicate that for most of the tested permutations, the required volume of the RRRs increased as the thresholds for peak and minimum hourly flows and the ramping rates became more stringent (Figure 2). The observed outcome can be attributed to two factors. Firstly, as the thresholds became more stringent, they activated the conditions that enable water storage by the algorithm at more time steps than those that facilitate water release. The flow pattern controls the algorithm's decision to store or release water. Secondly, a more stringent threshold necessitates storing or releasing larger quantities of water. Considering both factors, i.e., increased water storage events and an increased water volume to be stored in a singular event, led to the requirement of greater RRR volumes as the thresholds became more stringent. Nonetheless, for some permutations, this trend was not observed. One example is the needed reservoir volumes for P (10%, 3.5) and P (10%, 4) were larger than the reservoir volume needed for P (10%, 2.5) that had more stringent ramp rate threshold. For this particular case, the water released in proportion to the water stored for P (10%, 3.5) and P (10%, 4) was less efficient than that of P (10%, 2.5) due to algorithms increased propensity to store water rather than release water. As such, inadequate (i.e., too slow) water release back into the waterway might increase the required RRR volume or lead to small volume availability during high flows. Furthermore, if a flow adjustment of 10% is deemed sufficient, it is more beneficial then to consider permutation P (10%, 2.5) since it has more stringent ramp rate thresholds while requiring a smaller RRR volume. Whereas, if the daily peak and minimum flows are of greater concern than the ramp rates due to the ecological needs of the river, it would be more efficient to consider permutation P (20%, 4) than P (10%, 4) which requires a smaller RRR volume. The increased flow adjustment threshold in P (20%, 4) activated the conditions that enable water release by the algorithm at more time steps than those that allow water storage. Thus, resulting in a reduction of the required RRR volumes when compared to P (10%, 4). This highlights the significance of maintaining a proportional balance between storing and releasing water. As such, choosing the optimal re-regulation of reservoir volume is related to the river regime and sub-daily flow patterns. These findings highlight the importance of careful consideration of the unique characteristics of a given river and its ecosystem when designing RRRs for hydropeaking mitigation.

To achieve greater efficiency, RRRs can be optimized by tailoring their design to the ecological needs of the river and the desired mitigation objectives. Hayes et al. (2019), proposed a mitigation approach that is specific for the life cycle stages of fish. For instance, if the objective is to improve the larval life stage of trout and grayling rather than eliminating the stranding of fish, it might be more efficient then to have less stringent ramp rate thresholds resulting in the reduction of the required volume of RRRs. Another important factor to consider when optimizing the reservoir is the RRR operation period. It might be more efficient to adjust the threshold values and objectives according to the seasons, days, or time steps that are deemed significant to the ecological status of river rather than using constant threshold values for the whole year. Furthermore, excluding periods with less ecological significance from the operation period would reduce the required volume of RRRs. For the case studied in this work, excluding July and August from the operation period would be the most impactful on the required RRR volume as the highest flow occurs in the late spring or early summer. However, the re-regulation operation period should be tailored according to the ecological needs of the river in order to reduce the required RRR volume. Overall, these findings highlight the potential for optimizing the design and operation of RRRs for hydropeaking mitigation, based on the unique needs of the local ecosystem and the desired mitigation objectives. By doing so, a greater efficiency and a reduction in the required RRR volume, while minimizing the impact of hydropeaking on downstream ecosystem can be achieved.

The model design in this work can be used to determine the required RRR volumes for other HPP in any other river system of various sizes and flows. However, the range of thresholds for hydropeaking should be defined to best suit the flow pattern and river size. Furthermore, the model could be enhanced by incorporating additional conditions into the algorithm such as RRR operational period (season), timing of hydropeaking event (day and night), water temperature fluctuations, and sediment loads, while also accounting for water supply, irrigation, and recreational needs. Additionally, it may be useful to investigate a model with a RRR that is distant from the HPP. This would present the opportunity to study corridors connecting HPPs with RRRs as additional storage volumes. Also, a model that incorporates flow velocity and water losses from the RRR would further enhance the understanding, use, and optimization of RRRs.

Conclusion

We investigated in this work the capabilities of RRRs to limit flow components to a range of thresholds, such as peak flow, minimum flow, and ramping rates. The results indicate that as the thresholds become more stringent, the required RRR volume increase. In certain cases, however, this trend was not observed, indicating that the design of RRRs should be tailored according to mitigation objectives and ecological needs of river systems. The model developed in this study can aid HPP operators, authorities, and researchers in designing, optimizing, and rating the feasibility of introducing RRRs to river systems. However, several avenues for future research can be pursued to further advance the understanding, use, and optimization of RRRs. One promising area of investigation is the development of more sophisticated models that incorporate, RRR operational period (season), timing of hydropeaking event (day or night), as well as water temperature fluctuations and sediment loads. Finally, additional research is needed to better understand the ecological impacts of hydropeaking, including its effects on fish populations, water quality, and overall ecosystem health. By advancing our understanding of hydropeaking and its impacts, we can develop more effective strategies for managing our water resources and minimizing the negative impacts of hydroelectric power generation.

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Data Availability

The data that support the findings of this study are openly available in [Figshare] at 10.6084/m9.figshare.24786816.

Conflict of Interest

The authors of this paper certify that they have NO affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

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