Hydro-peaking mitigation measures: Performance of a complex compensation basin considering future system extensions

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Many Alpine rivers are affected by hydro-peaking, strong sub-daily fluctuations of discharge caused by intermittent power production from hydropower plants. Adding a retention volume at the outlet of a hydropower plant aims at attenuating hydro-peaking to a level where adverse effects on fish and invertebrates are minimal. The performance of such a retention volume needs to be assessed when extensions to the hydropower system are envisaged to improve operational flexibility. Using a set of scenarios for future power plant operation and a detailed operation model of the retention volume, future performance of a retention basin in Innertkirchen, Switzerland, is evaluated for the planned addition of a storage reservoir to the existing system. This particular retention basin is aiming at reducing the up- and down-surge rates, instead of focussing on limiting the ratio between base flow and peak flow. Three scenarios that assume that hydropower operation is driven by demand are developed, mimicking behaviour ranging from a rather smooth operation to an operation mode with extensive peaking. These scenarios are used in an optimisation model that simulates the operation of the retention volume for each time step based on limited knowledge of future inflows. After the addition of the reservoir, up- and down-surge gradients are expected to comply with threshold values derived from an extensive ecological field study. Increasing the lead time of power plant discharge from 30 minutes to 45 minutes could allow for improved management of the basin.

1 Background

In many Alpine rivers the flow regime is altered significantly by the construction of high-head storage hydropower plants (Meile et al. 2011). The two main drivers for change are transfer of water from summer to winter and strong sub-daily discharge fluctuations, called hydro-peaking. These fluctuations, caused by intermittent power production, can change the physical characteristics of the hyporheic habitat and entail severe negative impacts on aquatic ecosystems (Bruno et al. 2009). In Switzerland around 30% of all rivers with discharge monitoring in place, mainly large rivers in Alpine valleys, are affected by hydro-peaking (Limnex 2001). Water level fluctuations can have an amplitude between 0.1 and 2.5 meters (Limnex 2001). These fluctuations compromise riverine ecosystems by displacing fish and invertebrates downstream during flow increase and by increasing the risk stranding of fish during receding flows (Young et al. 2011).

Hydro-peaking can be mitigated through operational or structural measures. A simple operational measure is to increase the base flow in the river, either by increasing residual flow releases from the reservoir or by releasing water through the power plant at all times. An increased base flow lowers the ratio between low and high discharge, but might lead to production losses. Some power plants use a slower start-up or shutdown rate of turbines to mitigate hydro-peaking (Limnex 2001). Structural measures include the rerouting of the power plant outlet to a nearby lake or the construction of a compensation basin. The first compensation basins built in the 1960s provided a buffer for water release to the downstream river, aiming at reducing the ratio between high flows and the base flows in the river. The basin's volume was selected such that a constant flow release can be achieved. As mitigation strategies controlling the up- and down-surges become relevant, compensation basins are found to minimise hydro-peaking gradients at reasonable costs, while maintaining operational flexibility (Person et al. 2014).

With retreating glaciers in Alpine regions the hydrological regime will change, especially in summer (Terrier et al. 2011). Hydropower operators therefore face the challenge of constantly upgrading infrastructure to accommodate changed inflows to reservoirs and power plants. Moreover, retreating glaciers provide the potential for constructing new dams, adding to the total storage capacity (Terrier et al. 2011). Such system extensions will significantly impact the operation of hydropower plants and might compromise the performance of existing measures to mitigate hydro-peaking.

This article presents a methodology to assess future performance of a retention volume designed for hydro-peaking remediation. The methodology assumes that, in the future, the best possible operation strategies are implemented for the retention volume. Therefore, an optimisation approach is chosen to simulate future operation of the retention volume. As the retention basin is at the outlet of a complex hydropower system, it would be impractical to model the whole system. The assessment therefore relies on scenarios, outlining the potential future operation of the power plants discharging into the basin.

2 Case study Upper Aare valley

The hydropower system located in the Upper Aare River valley in Switzerland, operated by the Kraftwerke Oberhasli AG (KWO), consists of four major reservoirs and nine power houses. The power plants have an installed capacity of around 1’125 MW. The annual production is approximately 2 TWh, which accounts for roughly 5% of the total Swiss hydropower production. The operation of this system causes severe hydro-peaking in the Aare river at Innertkirchen, where discharge can vary between 3.0 m^3s^{-1} and almost 53 m^3s^{-1} during the low flow season between November and March (Schweizer et al. 2013a).

An assessment of the ecological state under a hydro-peaking regime, based on abiotic and biotic characteristics, identified the main disturbances. It was found that colonisation and reproduction of invertebrabes and fish are mostly influenced by large gradients of discharge rather than amplitude (Schweizer et al. 2013b). High positive gradients (up-surge) causes invertebrates to be drifted downstream, high negative gradients (down-surge) at low flows increases the risk of fish being trapped on gravel bars. Based on this assessment, maximum up- and downsurging rates are developed (Schweizer et al. 2013c). The construction of a retention basin with a volume of 80'000 m^3 is identified as a cost effective measure to remediate hydro-peaking (Schweizer et al. 2013d). A performance assessment showed that, with an actively operated basin, hydro-peaking is reduced to a level where ecologically justified discharge gradients are not exceeded (Bieri et al. 2014). In line with the extension project of one of the powerhouses discharging at Innertkirchen, the construction of such a retention basin was completed in autumn 2015. The basin will be fully commissioned in summer 2016.

For the current system the retention basin is expected to reliably reduce hydro-peaking (Bieri et al. 2014). This might, however, not be true after further extensions are built. One potential extension is the construction of a new reservoir at Trift (Fig. 1) following the retreat of the glacier. The addition of the Trift reservoir will provide storage capacity in the Gadmer valley, not available in the actual scheme. This will change the way power stations are operated. Since the Gadmerwasser cascade of power schemes also leads to Innertkirchen, adding Trift will have repercussions on the ability of the retention volume to attenuate hydro-peaking.

2.1 The KWO system

The Upper Aare Basin is located upstream of Lake Brienz in the canton of Bern in Switzerland. Around 20% of the total area of 554 km^2 is glaciated. The mean annual discharge at Meiringen, downstream of the power plants, is 35 m^3s^{-1}. Due to the high mean altitude (above 2000 m a.s.l.), discharge is mainly driven by snow and glacier melt. Since the early 20th century a hydropower scheme exploits the water resources in the Upper Aare valley. Four major reservoirs are located in the main Aare valley upstream of Innertkirchen. Electricity is produced along a cascade of power plants. The most downstream power house, Innertkirchen 1 (INN1), returns the water to the Aare river. As of summer 2016, when the extension of INN1 will be commissioned, the maximum discharge reaches 64 m^3s^{-1}. Within the eastern tributary valley of the Gadmerwasser river, several run-of-river power plants are installed in a cascade and water is returned the Aare river through the Innertkirchen 2 (INN2) power plant with a maximum discharge of 29 m^3s^{-1}. The Gadmer valley subsystem is depicted in Fig. 1.

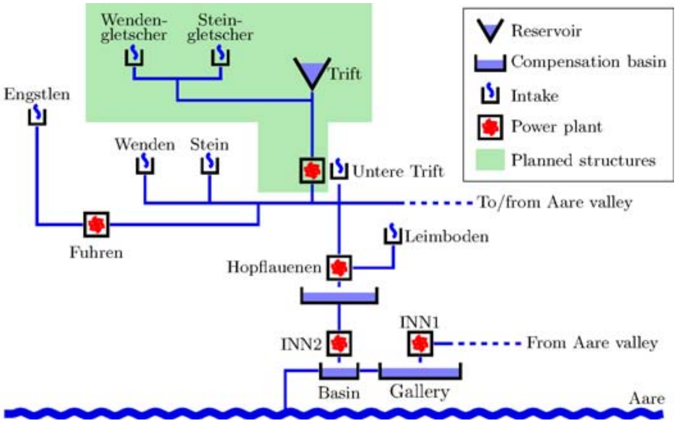


Fig. 1. Gadmer valley subsystem including planned addition of a reservoir at Trift.

2.2 Retention basin setup

To mitigate severe hydro-peaking caused by the two power plants INN1 and INN2, a retention volume was constructed and will be fully commissioned in summer 2016. Due to space constraints, the volume was built partly as an underground gallery with a volume of roughly 69’000 m^3 and an open-air basin with a volume of 20’000 m^3. The retention volume is actively operated. Two vertical gates between the gallery and the basin and one radial and one flap gate at the outlet of the basin allow to flexibly control discharge (Müller et al. 2014).

2.3 Hydro-peaking regulations

The main purpose of the present hydro-peaking remediation measures in the Aare valley is not to reduce maximum flows or the ratio between high and low flows, but to reduce the rate at which the water level increases or recedes. By limiting the rate of increasing discharge (up-surge), drift of invertebrates and fish is reduced. Positive discharge gradients are therefore limited to 0.7 $m^3s^{-1}min^{-1}$ (Schweizer et al. 2013c). Limits for negative gradients (down-surge) of -0.14 $m^3s^{-1}min^{-1}$ are only in effect during low flows, smaller than 8.1 m^3s^{-1}. This is justified by the increased risk of fish stranding on gravel bars, which are only exposed during low flows (Schweizer et al. 2013c). These gradient limits only apply during winter, from November 20 to March 10, when natural discharge is generally low. It is further defined that these gradient limits cannot be exceeded on more than 5% of days during the relevant period. Further, a global limit of ±2.5 $m^3s^{-1}min^{-1}$ is imposed, as defined in the license regulating exploitation rights.

2.4 Operational constraints

The design of the power plant also sets some constraints on how it can be operated. The Francis turbines installed at INN2 have an optimal efficiency at 75% of the design flow. With a maximum flow for one turbine $Q_{1,max}$=14.5 m^3s^{-1} and for two turbines $Q_{2,max}$=29 m^3s^{-1}, optimal efficiency is achieved at 10.9 m^3s^{-1} and 22.5 m^3s^{-1}, respectively. While the optimal efficiency does not impose a hard constraint on management, it can be anticipated that the turbines will be operated at the optimal flow whenever possible. A retention basin at Hopflauenen which has a volume of 58’000 m^3 (Fig. 1) allows for a somewhat independent operation of INN2 and the other power plants in the Gadmer valley.

2.5 The Trift extension

During periods of high glaciation in the Swiss Alps the Trift glacier widened a valley which leads into a bedrock sill, where the valley is relatively narrow. This bedrock sill provides a good location for the construction of a dam. The Trift reservoir will have its water level at an altitude of around 1767 m a.s.l. The foreseen live storage volume is 85×10^6 m^3. A new power plant will be built at the location of the existing water intake at Untere Trift at 1320 m a.s.l. (Fig. 1). This power plant will have an installed capacity of 80 MW and a design flow of 20 m^3s^{-1}. Two new water intakes will provide an average inflow of roughly 2.4 m^3s^{-1} into the Trift reservoir. The mean discharge of the Trift valley is expected to be just below 3 m^3s^{-1}. This means that the reservoir will retain roughly half of the expected mean annual inflows.

The Trift reservoir will provide storage in a part of the system (the Gadmer valley) which is now operated as run-of-river. It can be anticipated, that once storage is available in the subsystem, transfers from the Aare valley towards INN2 will not be as frequent anymore. Today, these transfers constitute the largest share of water used at INN2 between November and March.

3 Methods

3.1 Future inflow scenarios

The operation of the retention gallery and the retention basin at Innertkirchen is influenced by both, the INN1 and INN2 power plants. Thus, scenarios are developed for both power plants.

Scenario for INN1

It is assumed that the operation mode of INN1 does not significantly change once the Trift reservoir is added to the system. However, the hydropower operator will most likely stop the current practice of transferring water from the Aare valley to the Gadmer valley. The discharge of INN1 is therefore scaled with a factor, determined for each season, in order to accommodate the additional volume. For INN1 only one discharge scenario is derived and considered to be independent from the operation of INN2.

Scenarios for INN2

To anticipate future operation of INN2 three different scenarios were developed. Based on the historical operation pattern of existing storages in the Upper Aare valley, it was determined that between November and March 55×10^6 m^3 will be released from the Trift reservoir for all scenarios. These scenarios are not considered to provide an accurate depiction of future operation. They rather cover a range of potential operation patterns.

Scenario "Demand"

For this scenario, the total volume available during winter is released through the new power plant Untere Trift, when the total electricity demand in Switzerland is high. It is assumed, that water is released either at full capacity (20 m^{3}s^{-1}), or that the power plant is shutdown. In order to release the full volume, the power plant needs to run at full capacity for a certain time. To release a volume of 55×10^6 m^3, the turbine is running for roughly 770 hours or 31 days. From this duration, the corresponding quantile of the electricity demand duration curve is calculated (turbine duration divided by the length of the winter season). At the time where total electricity demand in Switzerland exceeds the threshold defined by the quantile, the discharge at Untere Trift is set to 20 m^{3}s^{-1}. Water diverted from water intakes present in the system is added to this discharge. This scenario serves as a proxy for an operation mode, where the whole cascade of power plants from Untere Trift to INN2 is used to cover the electricity demand. Discharge time series obtained with this scenario are further used as flow input to the retention basin at Hopflauenen for the following two scenarios, *Demand - Peak* and *Demand - Smooth*.

Scenario "Demand - Peak"

The assumption that the maximum discharge from INN2 will always be the discharge of maximum efficiency might not hold under future operation. This scenario is based on the assumption that, given a certain electricity demand, INN2 will be operated at the highest capacity rather than the highest efficiency. Also, with low electricity demand the turbines could be operated at lower capacities. As a proxy for the electricity output the production at INN1 is used (as provided by KWO). Discharges derived in scenario *Demand* are scaled between 50% and 100% based on discharges from INN1. As inflow to the basin Hopflauenen discharge obtained by the previous scenario is used. If the basin at Hopflauenen would run dry or overspill during the next time step, discharges are adjusted accordingly. This scenario can be considered as a rather extreme scenario, as high discharges from INN1 coincide with high discharges from INN2.

Scenario "Demand - Smooth"

This scenario models the same subsystem as the previous scenario. Instead of using INN2 for peak production, the basin at Hopflauenen is used to ensure that discharges at INN2 are always at the optimal capacity, 10.9 m^{3}s^{-1} for one turbine and 22.5 m^{3}s^{-1} for two turbines, respectively. Whether one or two turbines are operated is decided based on the water volume available in the basin Hopflauenen. The volume thresholds are defined such that the discharge at INN2 is constant for at least 3 time steps (45 minutes) if one turbine is used and 2 time steps (30 minutes) if two turbines are used. This scenario emulates a behaviour, where the INN2 power plant is operated exclusively at discharges with optimal turbine efficiency.

3.2 Basin operation

Operating a retention volume is a Markov decision process. At each time step a decision is taken to minimise or maximise a given objective, based on incomplete knowledge about future behaviour of the system and subject to the present state of the system. As soon as more information is available (at the next time step), the decision is revised based on newly available information in search for a smaller (or larger) objective value. A rolling horizon optimisation model that takes a decision at every time step based on the system state and information about future inflow is therefore well suited to simulate future behaviour of the system.

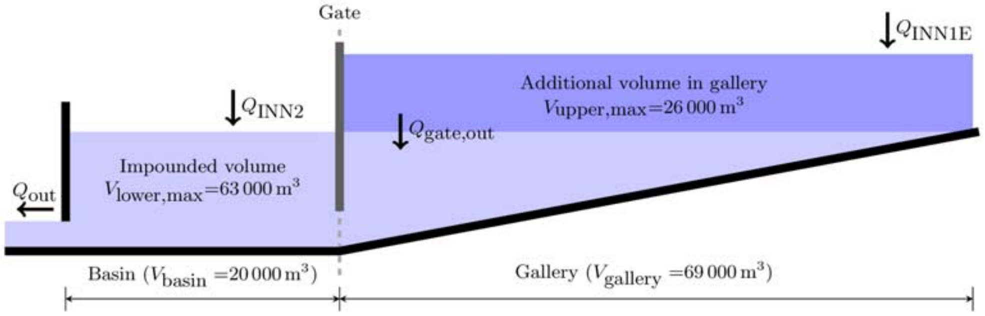


Fig. 2. Setup of the two volumes in the gallery and the basin at Innertkirchen.

The model accounts for the unique arrangement of the retention volume as a gallery and an open-air surface basin. Due to their direct hydraulic connection, the gallery and the basin are not operated independently. As long as the gate between the gallery and the basin is open, the water level in the basin is the same as in the gallery. Therefore, the basin and a part of the available retention volume in the gallery are operated as one single volume. Closing the gate between the basin and the gallery allows for a higher water level in the gallery and therefore provides additional storage capacity. In this model it is assumed that the gate is closed only when the maximum water level in the basin, and hence maximum storage in the common volume, is reached. It is further assumed that the flow through the gate can be controlled. As a simplification, no dynamic effects are considered. A schematic of the modelled system is depicted in Fig. 2.

Because of the short planning horizon of only 30 minutes, minimising gradients over this period might leave the retention volume in a state, where it cannot reliably cope with potential future inflows (i.e. almost empty or almost full). Instead, the optimisation approach presented here maximises the future operational flexibility of the retention volume. This is done by defining a target volume at the end of the planning horizon (t_{end}) which minimises the worst possible outcome. In the system there are two well defined states that qualify as worst possible outcome: (i) if the turbine flow reaches its maximum capacity over a long period, or (ii) if the turbines are shut down over a long period. The defined target volume is the volume (V_{target}) that maximises the time until the retention basin is full or empty, given the extreme inflow scenario.

The optimisation problem is formulated as follows:

$$\min_{Q_{out}(t)} \left(\frac{V_{lower}(t_{end}) + V_{upper}(t_{end}) - V_{target}}{V_{lower,max} + V_{upper,max}} \right)^2 + \sum_t \left(f_{neg}(J,t)\, f_{low\,flow}(Q,t) + f_{pos}(J,t) \right)$$

subject to

$$f_{neg}(J,t) \geq \begin{cases} 0, & \text{if } \; J(t) \geq -0.14\ \mathrm{m^3 s^{-1} min^{-1}} \\ a_{neg}\, J(t) + b_{neg} & \text{if } \; J(t) < -0.14\ \mathrm{m^3 s^{-1} min^{-1}} \end{cases},$$

$$f_{pos}(J,t) \geq \begin{cases} 0, & \text{if } \; J(t) \leq 0.7\ \mathrm{m^3 s^{-1} min^{-1}} \\ a_{pos}\, J(t) + b_{pos} & \text{if } \; J(t) > 0.7\ \mathrm{m^3 s^{-1} min^{-1}} \end{cases},$$

$$f_{low\,flow}(Q,t) \geq \begin{cases} 0, & \text{if } \; Q(t) \geq 8.1\ \mathrm{m^3 s^{-1}} \\ 1, & \text{if } \; Q(t) < 8.1\ \mathrm{m^3 s^{-1}} \end{cases}.$$

V_{upper} and V_{lower} are the volume stored in the upper and the lower compartment of the total storage, t_{end} denotes the lead time over which inflows are known. Q_{out} is the outflow of the basin to the river, Q(t) the total flow in the river and J(t) the discharge gradient in the river (including natural discharge). a_{neg}, b_{neg}, a_{pos} and b_{pos} are parameters used to define the linear constraint that acts as a punishment factor for exceeding hydro-peaking limits.

The target volume is defined as the volume that maximises the time elapsed before the basin is either completely full (t_{full}), or completely empty (t_{empty}), given the turbines are operated at full capacity, or completely shut down, respectively. The target volume V_{target}, t_{full} and t_{empty} can be calculated from the following three equations.

$$V_{target} = \int_{t_{end}}^{t_{empty}} Q_{out}\, dt,$$

$$V_{lower,max} + V_{upper} - V_{target} = \int_{t_{end}}^{t_{full}} Q_{in.max}\, dt - \int_{t_{end}}^{t_{full}} Q_{out}\, dt,$$

$$t_{empty} = t_{full}.$$

The optimisation model is run for a forecast horizon (t_{end}) of 30 minutes and for 45 minutes. In other words, the optimisation algorithm tries to reach the target volume after 30 minutes or after 45 minutes. It is expected that a longer forecast time leads to a better management with fewer events where hydro-peaking gradient limits are violated.

In this study it is assumed that the discharge regime defined by the optimisation model can be implemented in reality by operating the gates of the basin accordingly.

3.3 Implementation

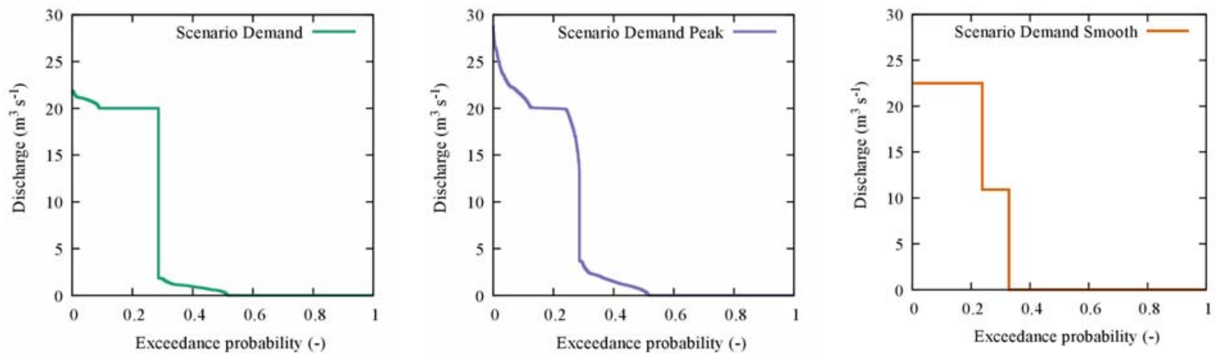
The scenario computation and the optimisation model is built using the Python programming language and Pynsim, a network simulation library (Knox et al. 2016). The optimisation problem is implemented using Pyomo (Hart et al. 2011) and the couenne non-linear solver (Belotti et al. 2009).

3.4 Data

All discharge data used in this study was provided by the power plant operator (KWO) at a 15-minute time step. All scenarios and the basin operation model are evaluated between November 20 and March 10 in the years 2009 through 2014. Electricity demand data for Switzerland is provided by Swissgrid at a 15-minute time step (Swissgrid 2016).

4 Results and Discussion

4.1 Scenarios

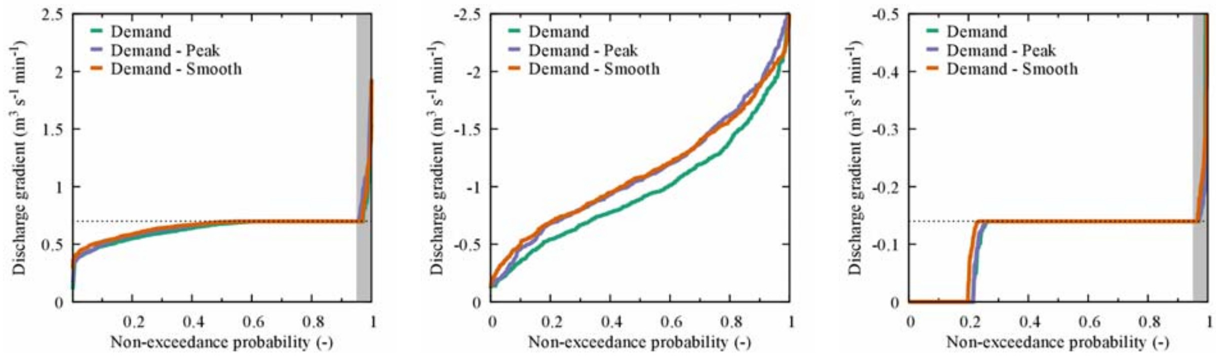


(a) *(b)* *(c)*

Fig. 3. Duration curves of discharge at INN2 for scenario Demand (a), Demand - Peak (b) and Demand - Smooth (c).

The duration curves of the three discharge scenarios at INN2 are shown in Fig. 3. These scenarios show very distinct patterns. The scenario based solely on electricity demand (Fig. 3(a)) features discharges of 20 m^3s^{-1} most of the time. The reason for this is the design flow of the new power plant at Trift, which is planned to be 20 m^3s^{-1}. In scenario Demand - Peak (Fig. 3(b)), this pattern is less pronounced, since discharges are scaled based on production at INN1. This leads to generally higher discharge fluctuations. Scenario Demand - Smooth (Fig. 3(c)) leads to a discharge pattern, where only two different discharges are observed (10.9 m^3s^{-1} and 22.5 m^3s^{-1}). The retention basin upstream of INN2 provides a sufficient volume to operate the turbines at INN2 at their optimal capacity. All three scenarios comply with the physical constraints of the system, such as limited flow capacity. Because the retention basin at Hopflauenen decouples the power plant cascade of the Gadmer valley and because INN2 is the least flexible power plant in the system, it can be anticipated that this basin might be used as intermediate storage in the future. Therefore, a scenario based only on demand (scenario Demand), where the whole power plant cascade is operated as one big power plant seems to be the least likely future operation mode.

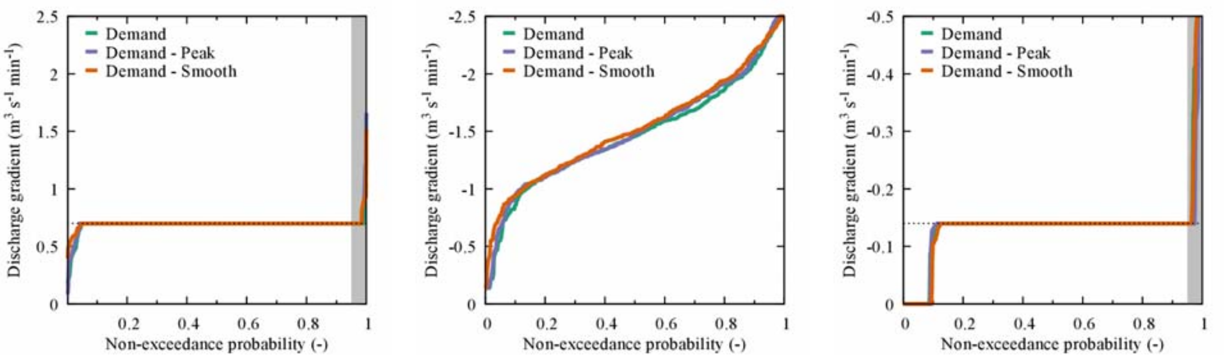
4.2 Basin operation



(a) *(b)* *(c)*

Fig. 4. Non-exceedance probabilities of daily maximum gradients for all scenarios and 30 minutes lead time for positive gradients (a), negative gradients (b) and negative gradients during low flows (c).

Fig. 4 shows the non-exceedance probability for daily maximum gradients for each of the scenarios if the discharge from INN1 and INN2 is known 30 minutes ahead. In none of the scenarios the hydro-peaking limit is violated on more than 5% of all days (grey shaded area). Although the scenarios provide very different operation modes with pronounced discharge peaks, the resulting flow regime at the outlet of the basin is very similar for all scenarios. On around 50% of all days the positive hydro-peaking gradient limit is not reached. This means that there is some headroom left for reliably attenuating more pronounced peaking discharges from INN1 and INN2. During low flow periods the negative gradient limit is reached at about 70% of all days in the relevant season and no negative gradients occur 20% of the time. This can be explained by the fact that a relatively large volume needs to be released if negative gradients are to be minimised during low flows. An optimal operation strategy therefore aims at preserving as much of the available volume as possible, which is equivalent to regulating water releases to follow the lowest possible gradient.



(a) (b) (c)

Fig. 5. Non-exceedance probabilities of daily maximum gradients for all scenarios and 45 minutes lead time for positive gradients (a), negative gradients (b) and negative gradients during low flows (c)

Fig. 7 shows the non-exceedance probability of daily maximum gradients if the lead time of discharge from INN1 and INN2 is 45 minutes. It can be noted that the positive gradient limits are violated less often. In turn the limit is reached most of the time. With a longer lead time, the basin is operated in a more dynamic way, where the limits are rarely exceeded at the expense of reaching the limits more often. Again, the probability distributions are very similar for all scenarios.

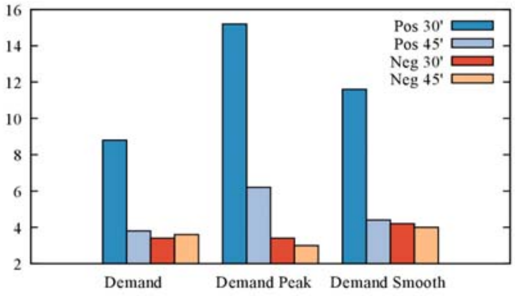


Fig. 6. Number of times positive and negative discharge gradients are exceeded for all scenarios (average per season).

The number of (15 min) time steps where gradients are exceeded is shown in Fig. 8, based on a lead time of 30 and 45 minutes, respectively. The reduction of positive gradient violations is much more pronounced than the reduction of negative gradient violations during low flows. For an effective reduction of negative gradients, a large water volume is required. Reducing the outflow of the basin from 8 m^3s^{-1} to 3 m^3s^{-1}, while respecting gradient limits, takes more than 35 minutes and uses a volume of 12’000 m^3. This limits the operational flexibility of the basin for reducing negative gradients.

5 Conclusions

With planned extensions of existing hydropower schemes, there is a need for assessing the robustness of existing and planned infrastructure for hydro-peaking mitigation. In the Upper Aare valley, hydro-peaking is attenuated by a retention volume at the outlet of two power plants. One prerequisite for the assessment are scenarios for potential future discharge signatures. Based on a simplified system representation and a set of rules, meaningful scenarios are developed, which cover a range of potential future operation of the system. These scenarios are used as input for an optimisation model that anticipates the best possible operation of the retention basin under future conditions. Due to the short lead time for which power plant discharge is known, the optimisation maximises future flexibility rather than minimising gradients. It is shown, that under all assessed future operation scenarios the basin is able to attenuate hydro-peaking respecting the agreed thresholds. With a longer lead time for which inflows to the retention basin are known the number of discharge gradient violations can be reduced effectively.

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