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Flow restoration in Alpine streams affected by hydropower operations—a case study for a compensation basin

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ABSTRACT: Hydropeaking, resulting from rapid starting and shut-down of turbines, is one of the major hydrological alterations in Alpine streams. The upper Aare River basin in Switzerland comprises a complex high-head storage hydropower scheme. The significant turbine capacities of the two downstream powerhouses produce severe hydropeaking in the Aare River. To reduce the negative impact of the foreseen increase of the turbine discharge, a compensation basin combined with an extended tailrace tunnel downstream of the powerhouses has been designed and is under construction now to facilitate lower flow ramping increasing time for aquatic species to react. The design of the basin and its overall operation had to be defined to reach best ecological as well as economic performance. The retention volume and the operation rules of the basin have been optimized to avoid dewatering of juvenile brown trout. Further, flow ramping has to be limited in order to reduce drifting of macroinvertebrates. The paper presents a consistent approach of a target-oriented process management, including modelling, simulation and comparison of future flow regime without and with mitigation measure. Finally, rules for decision-making as well as the prototype's final design are addressed.

1 INTRODUCTION

Since 1950, a large number of high-head storage Hydropower Plants (HPPs) in the Alps have supplied peak load energy to the European power grid (Schleiss 2007). In Switzerland, for example, 32% of the total electricity in 2010 was produced by storage hydropower plants. Water retention in large reservoirs and concentrated turbine operations allow electricity to be produced on demand. The sudden opening and closing of the turbines produces highly unsteady flow in the river downstream of the powerhouse (Moog 1993). This so-called hydropeaking is the major hydrological alteration in Alpine regions (Petts 1984, Poff et al. 1997). Due to the unpredictability and intensity of flow change, sub-daily hydropeaking events disturb the natural discharge regime, a key factor in ecological quality and the natural abiotic structure of ecosystems (Parasiewicz et al. 1998, Bunn and Arthington 2002). These disturbances directly affect riverine biological communities (Young et al. 2011). Frequent and rapid fluctuations change hydraulic parameters, such as flow depth, velocity and bed shear stress (Petts and Amoros 1996), and thus influence habitat availability, stability and quality.

After decades of the extensive use of water resources, with severe consequences for aquatic and riverine biota, governments have begun to recognise the need for a water protection policy, e.g. the European Union Water Framework Directive. In Switzerland, Parliament adopted the Law on Water Protection in 2011 to improve the quality of Swiss waters, including hydropeaking mitigation.

In a first step and according to an upgrading programme of the hydropower scheme of the Kraftwerke Oberhasli (KWO), the flow regime of the upper Aare River in Switzerland should be improved and thus the hydrological deficit reduced. Several studies (Schweizer et al. 2010, 2012, 2013a, b, c, d) have analysed the aquatic habitat conditions regarding the recently published guidelines of the Swiss Confederation (Baumann et al. 2012). Ecological conditions are supposed to get significantly improved by a reduction of up- and down-ramping rates respectively. A comparison of several mitigation alternatives (Person et al. 2014) revealed a compensation volume between the turbine releases of the Innertkirchen 1 and 2 HPPs and the Aare River as ecologically and economically most effective. The goal of the herein presented study is, on the one hand, to define needed retention volume as well as the operation rules by an optimization algorithm and, on the other hand, the detailed layout of the mitigation measure, consisting of a retention basin combined with an extended tailrace tunnel of the Innertkirchen 1 HPP. Simplified conditions had to be re-evaluated for prototype's design and implementation. The following chapters mainly focus on the challenging step from the preliminary modelling to final design of the first hydropeaking retention basin in Switzerland, assessed according to the new hydropeaking guidelines of the Swiss Confederation.

2 CASE STUDY

Figure 1 shows the upper Aare River basin located upstream of Lake Brienz in the centre of the Swiss Alps. The surface area is 554 km^2, of which about 20% is glaciated. The natural hydrological regime of the Aare River, with a mean annual discharge of 35 m^3/s, shows low discharge in winter and high runoff in summer due to snow and glacier melt. The mean catchment altitude is 2150 m a.s.l. The Aare River, also called the Hasliaare at its headwaters, has its source in the Unteraar and Oberaar glaciers (Schweizer et al. 2008).

Since the early 20th century, a hydropower scheme of nine powerhouses and several reservoirs and intakes has been constructed. The Kraftwerke Oberhasli (KWO) Company utilises 60% of the catchment area for hydropower. KWO has a total installed capacity of 650 MW

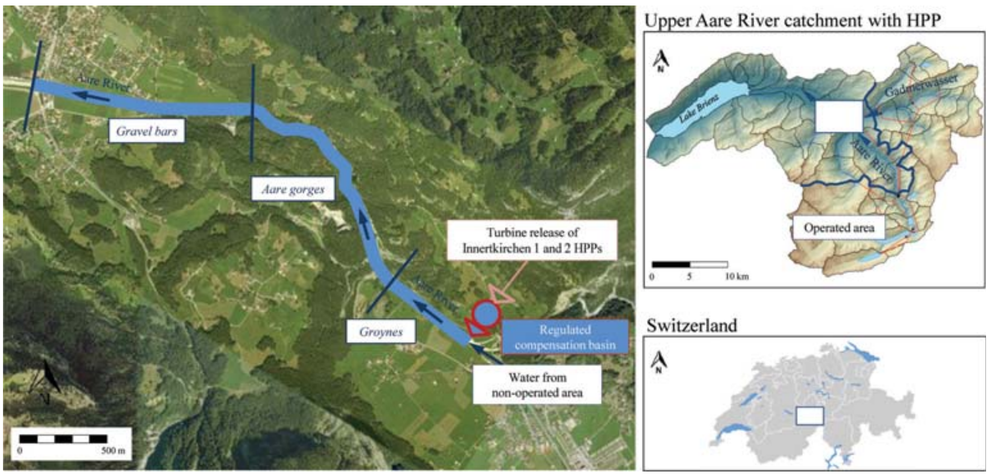

Figure 1. Aare River reach downstream of tailrace tunnels of Innertkirchen 1 and 2 hydropower plants and its location in the upper Aare River catchment upstream of Lake Brienz and in Switzerland.

and generated 1750 GWh (without pump-storage) in 2010, corresponding to approximately 10% of the Swiss hydropower output. The water from the Aare catchment flows through the artificial reservoirs of Oberaar, Grimsel, Räterichsboden and Handeck. In Innertkirchen, the water is returned to the Aare River by the Innertkirchen 1 HPP. The River Gadmerwasser drains the eastern part of the basin (Susten). After driving the turbines, the water is released from the tailrace of Innertkirchen 2 HPP to the Hasliaare River. The substantial turbine capacities of the Innertkirchen 1 and 2 HPPs of 39 and 29 m^3/s respectively produce severe hydropeaking in the downstream river. An upgrading programme for the entire scheme, called KWO*plus*, comprises a large number of technical, economic and ecological improvements to the scheme. To compensate for the turbine capacity increase of Innertkirchen 1 HPP by 25 m^3/s, a compensation basin downstream of the powerhouse outflow is planned for reduction of flow up- and down-ramping rates.

In the 19th century, the dynamic braided river network of the Hasliaare River was drained for agricultural use and flood control. A mostly straight channel resulted from the pristine braided network because of the successive river channelisation. Based on the three parameters of variability of water surface width, bank slope and mesohabitat, the reach downstream of the powerhouse outlets can be divided into four reference morphologies: a reach with artificial groynes (650 m), the Aareschlucht Canyon (1.4 km), a reach with alternating gravel bars (1.3 km) and a monotonous and straight channel reach (11 km). The dewatered reach upstream of Innertkirchen, which carries residual flow, has in its upstream part a natural morphology. Mainly the gravel bars still show natural morphology with varying instream structure.

The condition and type of habitat influence species diversity, growth rates and abundance of aquatic fauna and flora. Several studies have been performed for analysis and understanding of the ecosystem of the Hasliaare River (Schweizer et al. 2010, 2012, 2013a, b). Fish as well as benthos are especially relevant regarding hydropeaking. The quality of the aquatic habitat of the Hasliaare River has decreased during the last 150 years. The dynamic braided river network with various mesohabitats gave way to a mainly straight and monotonous channel without any instream structure. Since the 1930s, the natural flow regime of the river network in the upper Aare River catchment has been altered by high-head storage schemes. Seasonal water transfer from summer to winter and an increased frequency of daily peak discharge events result. Abundance and biomass of fish and benthos have decreased due to the negative influences. Despite today's situation of aquatic biota, the potential for biological development of the Hasliaare River has been highlighted. Investigations to improve the river morphology and the flow regime have been therefore recommended.

3 METHODS

Figure 2 shows the main steps of the procedure of the evaluation and implementation of a hydropeaking mitigation measure. The analysis of the Hasliaare River highlighted beside the morphological deficits a hydrological mitigation potential. Thus, the retention volume between the tailwater of the Innertkirchen 1 and 2 HPPs and the stream, consisting of a basin and a tunnel, should allow (1) minimizing up-ramping and thus macroinvertebrates' drifting and (2) dampening of down-ramping, avoiding dewatering of juvenile brown trout in the gravel bars reach for low flows (<8.1 m^3/s).

4 HYDROLOGICAL SIMULATION

4.1 *Flow up- and down-ramping*

Hydropeaking is mainly critical in winter due to generally low runoff from the catchment area. Thus, the study focused on winter periods between mid-November and mid-March from 2009 to 2012. For the four winter periods, 15-minutes data series of Innertkirchen 1 and 2 turbine release in addition to the runoff from the non-operated catchment have been considered.

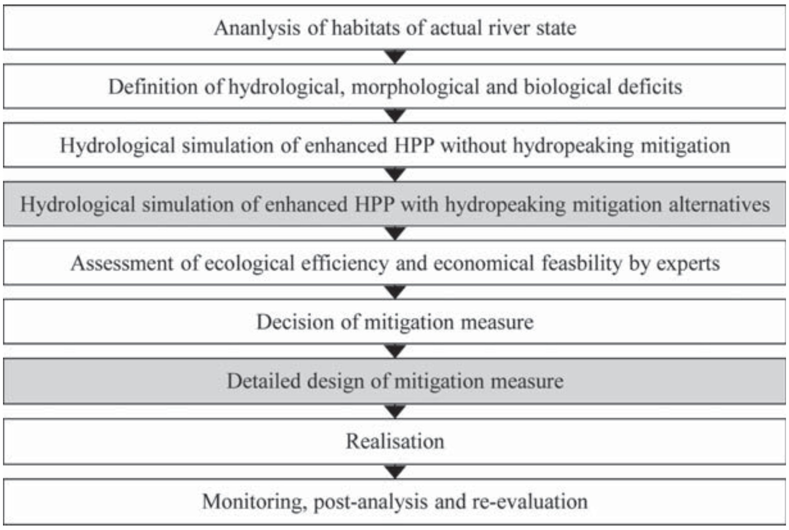

Figure 2. Methodology of definition, design, realisation and monitoring of hydropeaking mitigation measures as applied for the upper Aare River catchment.

As the turbine capacity of the Innertkirchen 1 HPP of 39 m^3/s is increased by 25 m^3/s in the framework of the upgrading programme KWO*plus*, data series of future operation had to be generated. When the sum of the Innertkirchen 1 and 2 release was greater than 55 m^3/s, full 25 m^3/s were added. For values smaller than 35 m^3/s, no additional release was considered. In between, proportional addition was applied.

The goal of dampening of flow ramping is not to reduce peak discharge Q_{max} or increase off-peak discharge Q_{min}, but to achieve flow change over a longer time lap and thus to reduce the flow gradients. The flow ramping rate $\Delta Q(t)$ [$m^3/s/min$] indicates the discharge increase or decrease respectively over a given time step, whereas up-ramping generates positive values and down-ramping negative ones:

$$\Delta Q(t) = \frac{Q(t) - Q(t - \Delta t)}{\Delta t} \tag{1}$$

where $Q(t)$ = discharge at moment t; $Q(t–\Delta t)$ = discharge at moment $t–\Delta t$; and Δt = time step.

The flow level ramping rate $\Delta H(t)$ [cm/min] indicates the change of flow level:

$$\Delta H(t) = \frac{H(t) - H(t - \Delta t)}{\Delta t} \tag{2}$$

where $H(t)$ = flow level at moment t; $H(t–\Delta t)$ = flow level at moment $t–\Delta t$; and Δt = time step.

In the given case, up- and down-ramping had to be distinguished, as involved in different biological phenomena. Further, a comparison of the hydrographs immediately downstream of the powerhouses and at the gravel bars reach allowed the definition of the morphology induced damping effect of the corresponding river reaches. Ramping rates of the generated flow series could be correlated to the downstream ones.

Down-ramping is only crucial for the gravel bars reach, as only there dewatering of brown trout is a risk. 2D hydrodynamic simulations allowed the definition of flow level down-ramping rates from the generated flow series for the two cross-sections. As a result dewatering is thus only a problem between 8.1 and 3.1 m^3/s. The guidelines (Baumann et al. 2011) define a maximum flow level down-ramping of –0.5 cm/min.

4.2 *Operation*

Today's as well as future's flow regime should be compared to flow regime influenced by retention volumes. For the parameter study volumes of 50'000, 60'000, 80'000 as well as 100'000 m^3 have been modelled, operated and compared. The whole turbine release from the Innertkirchen 1 and 2 HPPs is given to the compensation volume, which has to be operated reducing up- as well as down-ramping and guarantee a minimum discharge of 3.1 m^3/s. To reduce down-ramping, water should be retained in the basin and released as slowly as possible. Doing this too slowly, only little volume would be available in case of starting turbines and up-ramping could be reduced less efficiently. Turbine release was just given for one time step of 15 minutes. Two scenarios have been set up and assessed:

– *Scenario A* minimises the up-ramping rate by respecting today's down-ramping rates.
– *Scenario B* optimises firstly the down-ramping for low flows and secondly the up-ramping rate. To guarantee enough retention volume for down-ramping for low flows, a volume of 12'000 m^3 is retained.

The comparison between the different alternatives has been undertaken with the 95%-percentile of daily maximum values.

4.3 *Results*

For today's scheme and for winter conditions of 2009 to 2012, the flow up-ramping rate is 1.36 m^3/s/min (Fig. 3a). The flow level down-ramping rate for discharges below 8.1 m^3/s of –2.5 cm/min for the gravel bars reach (Fig. 3c) is much higher than the recommended limit value of –0.5 cm/min in the guidelines (Baumann et al. 2012).

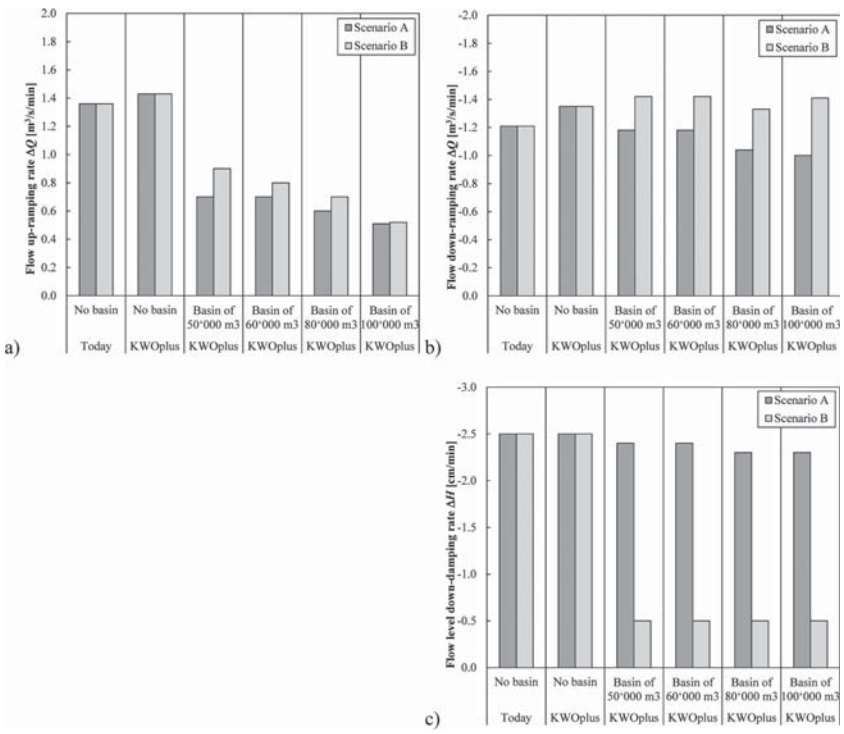

Figure 3. Flow regime characteristics for today's and the enhanced Innertkirchen 1 HPP (KWO*plus*) without and with retention volumes for scenarios A and B for winter conditions from 2009 to 2012: 95%-percentile of (a) flow up-ramping rate and (b) down-ramping rate immediately downstream of the outlet of the retention volume; and (c) flow level down-ramping rate for flows below 8.1 m^3/s for the gravel bars reach.

Increasing the discharge capacity of Innertkirchen 1 HPP by 25 m³/s, flow up-ramping rates would slightly increase compared to today's values (Fig. 3a). The down-ramping rate as well as the flow level down-ramping value for discharges below 8.1 m³/s remain the same (Fig. 3b and c).

Scenario A shows the reduction ability of flow up-ramping of increasing retention volume, from 1.36 (today) and 1.43 m³/s/min (KWO*plus*) to values of 0.70 and 0.51 m³/s/min for 50'000 and 100'000 m³ retention capacity respectively (Fig. 3a). The down-ramping rates generally decrease (Fig. 3b). The compensation volume allows also to reduce extreme values (100%-percentile). The smallest volume of 50'000 m³ would decrease the flow up-ramping rate from today 2.43 to 1.06 m³/s/min and increase the down-ramping rate from –2.82 to –1.49 m³/s/min.

Scenario B is able to reduce flow level down-ramping for flows below 8.1 m³/s for the gravel bars reach in any case to –0.5 cm/min, achieving the implemented threshold value (Fig. 3c). It reduces flow up-ramping rates to values of 0.90 and 0.52 m³/s/min for 50'000 and 100'000 m³ retention capacity (Fig. 3a). Extreme values are also affected. The order or magnitude is slightly lower than for scenario A, as 12'000 m³ of the volume are used for low flow down-ramping.

Based on the generated data and the construction cost estimates, an expert panel of environmental specialists, engineers, representatives of cantonal and federal authorities as well as the owner assessed the alternatives by a cost-benefit-analysis. Finally, the 80'000 m³ alternative has been selected as the most convenient compromise, acceptable for all of the involved partners.

5 DETAILED DESIGN

The enhancement of the existing Innertkirchen 1 HPP in the framework of KWO*plus* consists of an additional headrace tunnel and powerhouse, called Innertkirchen 1E, which is actually under construction. From the surge tank, a second pressurised shaft guides water toward the new Innertkirchen 1E powerhouse (Fig. 4). The existing tailrace tunnel will be connected to the new one and will be closed by a bulkhead gate at its downstream end. Thus,

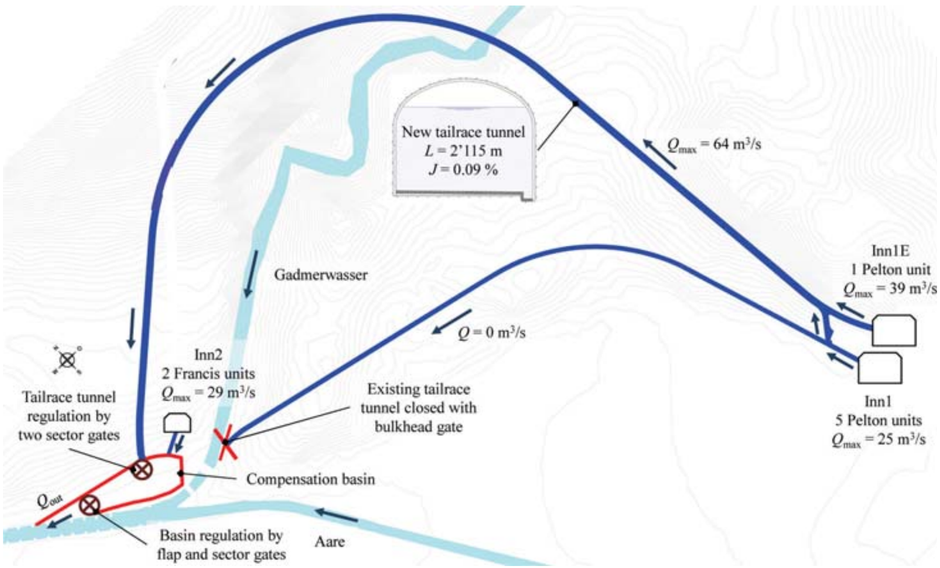

Figure 4. Sketch of the hydraulic system of the compensation basin and the new tailrace tunnel of the enhanced Innertkirchen 1 HPP (Inn 1 and Inn 1E) and the Innertkirchen 2 HPP (Inn 2).

the released water of the enhanced HPP will flow through the new tailrace tunnel into the compensation basin.

Based on the results of the hydrological simulation and in the framework of the realisation of the HPP enhancement, the IUB Engineering Ltd. has studied several alternative concepts for the compensation basin. As the on-site conditions do not allow the construction of a surface basin of the required volume of 80'000 m^3, the new 2.1 km-long tailrace tunnel between the Innertkirchen 1E powerhouse and the basin is extended to provide extra volume and to actively contribute to compensation of flow variations from the turbines. Two sector gates at the downstream end of the tailrace tunnel as well as a flap gate and a sector gate at the outlet of the compensation basin allow operation of the two storage volumes.

5.1 *Regulation strategy*

In addition to the preliminary simulations, which basically considered the ecological requirements and one homogenous volume for flow regulation, the detailed design had to deal with system and operation constraints given by the plant operator KWO. Based on instantaneous $Q_{in}(t_0)$ as well as predicted $Q_{in}\,(t_1) = Q_{in}\,(t_0 + 15')$ turbine discharge of Innertkirchen 1, 1E and 2 HPPs, the instantaneous discharge released to the Aare River by the compensation basin $Q_{out}(t_0)$ and the stored volume $V(t_0)$, the regulation algorithm calculates the discharge $Q_{out}(t_1)$ which has to be released during the next time step, taking into account:

- *Priority 1—System reliability and safety*: Released outflow $Q_{out}(t_1)$ would neither empty the basin nor lead to its overflow within the next time step. As the tailrace tunnel is long, routing effect leads to flow propagation time of 7 minutes. When high inflow is predicted, the control gates of the basin have to be opened for preliminary water release in order to ensure the up-ramping rates. However, during the period of pre-up-ramping, the basin itself should not be emptied.
- *Priority 2—Maximum up- and down-ramping rates:* Up-ramping rate is limited to 2.5 m^3/s/min and down-ramping rate to –2.5 m^3/s/min for discharge higher than 8.1 m^3/s and to –0.14 m^3/s/min for low flows.
- *Priority 3—Operation flexibility*: The released discharge $Q_{out}(t_1)$ is set, that is within the next two time steps of 15 minutes (t_2) operation can either be stopped to $Q_{in}(t_2) = 0$ m^3/s or increased to full capacity $Q_{in}(t_2) = Q_{max} = 93$ m^3/s.
- *Priority 4—Desired up- and down-ramping rates*: Up- and down-ramping rates, which are ecologically desired but not crucial for species survival, are taken into account by the regulation whenever possible.

Based on these regulation rules, the retention volume is managed. The boundary conditions define a range of possible released discharges $Q_{out}(t_1)$. Within this range, the regulation algorithm calculates the optimum discharge with respect to the inertia of the system as well as the upper and lower discharge limits, improving the regulation performance.

A regulation at high inertia leads to no or very small discharge variations as long as the operation flexibility and the system safety are not affected. Thus, the retention volumes are exploited to a maximum, as they are filling or emptying until the prioritised boundary conditions become relevant. On a technical level, this results in less but bigger regulation movements of the gates. However, when the system reaches its limits, i.e. the prioritised boundary conditions become relevant, flow changes between two time steps are big and thus up—or down-ramping rates are reaching values close to the maximum of 2.5 m^3/s/min. Low inertia requires a higher technical complexity of gate control but leads to faster adaptation of released discharge between two time steps. Thus, the operation and system safety boundary conditions are reached less often as the regulation reacts more rapidly on flow changes from the HPPs.

The upper and lower discharge limits are defined by maximum and minimum turbine discharges forecasted by the plant operator, by taking into account daily forecasts of power production. Thus, this discharge spectrum can be considered as an additional boundary condition for the regulation algorithm, with the priority 5. The released discharge $Q_{out}(t_1)$ is

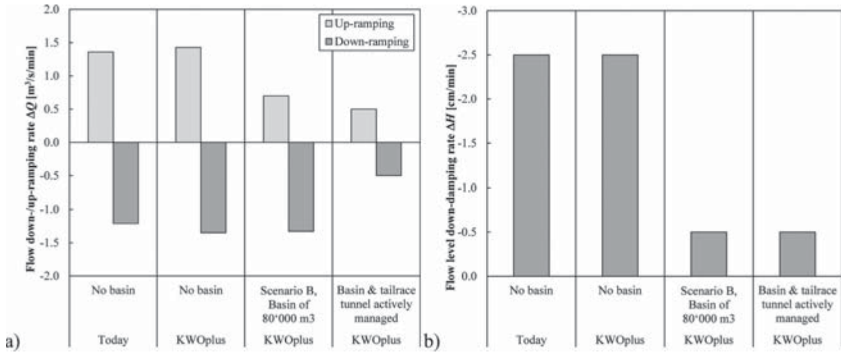

Figure 5. Flow regime characteristics for today's and the enhanced (KWO*plus*) Innertkirchen 1 HPP without retention volume, with one homogeneous retention volume of 80'000 m^3 (Scenario B) and with active volume management for both basin and tailrace tunnel for winter conditions from 2009 to 2012: 95%-percentile of (a) flow up- and down-ramping rates immediately downstream of the outlet of the retention volume and (b) flow level down-ramping rate for flows below 8.1 m^3/s for the gravel bars reach.

defined within this predicted discharge spectrum whenever possible, i.e. as long as no other boundary condition becomes determinant.

5.2 *Results*

The regulation performance is again given as the 95%-percentile of daily maximum values. Results reveal that even under operation and reliability constraints, flow up- and down-ramping rates can be considerably reduced compared to today's values or the rates expected after the enhancement of the Innertkirchen 1 HPP (KWO*plus*).

By actively managing the two storage volumes of the basin and the tailrace tunnel, the up-ramping rates can be reduced from 1.36 $m^3/s/min$ (today) and 1.43 $m^3/s/min$ (KWO*plus*) to 0.50 $m^3/s/min$ under optimum regulation parameters. The down-ramping rates are decreased to –0.50 $m^3/s/min$ for flows above 8.1 m^3/s (Fig. 5a). For discharges below 8.1 m^3/s, flow level down-ramping in the gravel bars reach is reduced to –0.5 cm/min, achieving the implemented threshold value (Fig. 5b).

The trailrace tunnel regulation is most effective for low turbine discharges when the unregulated volume occupied by the normal water depth is low and a considerable additional volume can be generated by closing the sector gates at the downstream end of the channel. This is especially important from an ecological point of view, as the flow level variations in the downstream gravel bars reach can be limited to ensure the conditions required for the brown trout during winter, when turbine discharges are generally low.

6 DISCUSSION

The increase of the turbine capacity of the Innertkirchen 1 HPP would increase the flow up- as well as down-ramping rates in the upper Aare River. A compensation volume, installed between the powerhouse and the release to the river, allows mitigation of these negative effects. To maximise its benefits, the operation rules have to focus on specific ecologically defined threshold values. In the given case, hydrological time series could have been produced for decision-making, taking into account different retention volumes and operation scenarios.

In a first step, the effect of one homogeneous retention volume on flow compensation has been studied. Even a small volume of 50'000 m^3 allows a reduction of the up-ramping rate from 1.43 with KWO*plus* to 0.9 $m^3/s/min$ as well as of the flow level down-ramping rate in the ecologically relevant gravel bars reach from –2.5 to –0.5 cm/min, fulfilling the targets of the guidelines. However, a retention volume of 80'000 m^3 has been defined as most suitable.

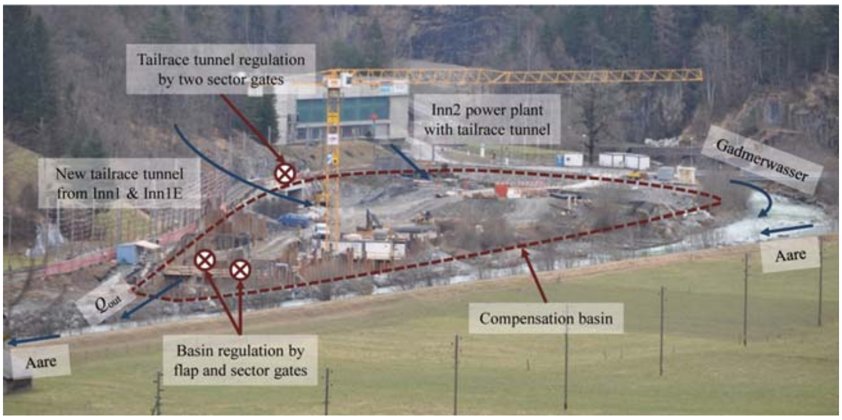

Figure 6. Construction site of the compensation basin in Innertkirchen (picture courtesy of KWO, January 2014).

According to the results of the preliminary study, this alternative results in up- and down-ramping rates of 0.7 and –1.33 $m^3/s/min$ as well as in a down-ramping rate in the ecologically relevant gravel bars reach of –0.5 cm/min.

In a second step, corresponding to the design phase of the enhancement project, the site conditions as well as additional system and operation requirements have been considered. The flow regulation downstream of the powerhouses is guaranteed by two retention volumes, namely the tailrace tunnel and the compensation basin, which are actively managed by gates. Under optimum regulation control, up- and down-ramping rates of 0.5 and –0.5 $m^3/s/min$ as well as a down-ramping rate of –0.5 cm/min in the gravel bars reach could be achieved for the given discharge series for winter conditions from 2009 to 2012. Up- and down-ramping rates could be improved by the developed design and the corresponding operation rules.

The chosen approach is straight forward. It focuses on the implementation of the mitigation measure. Target species as well as specific hydrological and morphological conditions of the Hasliaare River have been addressed. Several assumptions had to be made during the final design of the retention basin and tunnel, generating uncertainty regarding results. Future turbine operation is related to past winter conditions of 2009 to 2012, which may not fully correspond to future production process. The applied operation flexibility defined during detailed design should be able to address future changes in the schedule. Furthermore, future river restoration projects should consider the modified flow regime, avoiding dewatering of fish and its spawning ground. The system, as defined by the herein presented approach, is under construction now (Fig. 6). A monitoring system will allow assessing the performance and optimising system operation accordingly. Re-evaluation of the operation schedule has to be done continuously by addressing hydrological, plant operation, morphological and habitat conditions.

Nevertheless, flow regime mitigation is only successful with suitable river morphology and vice versa. Habitat simulations show that hydropeaking impact is strongly dependent on river morphology. Similar to many rivers in mountainous catchment areas, the Hasliaare River has undergone considerable anthropogenic changes. Construction mitigation measures, such as the compensation basin, would even show higher ecological performance for a naturally braided morphology. Thus, several river widening projects as well as instream improvements are under evaluation in the framework of flood management projects and KWO*plus*.

7 CONCLUSION

The applied method for flow restoration in the upper Aare River in Switzerland is presented, containing the definition of river specific habitat criteria, hydrological simulations as well as the detailed design of the retention basin. Flow restoration in Alpine streams affected by hydropower operations ask for specific indices for an appropriate assessment of the hydropeaking impact on aquatic habitat. For effective flow regime mitigation, restoration of the altered morphology is essential. The study may help to support the application of the Law on Water Protection for river restoration projects at existing and newly developed hydropower facilities in Alpine areas, showing beside conceptual approaches also realisation focused engineering.

The applied approach allows operators of hydropower plants, authorities or researchers to analyse impacted river systems, to design and rate ecologically and economically retention measures. Thus hydropeaking can be addressed in an optimal manner, as shown for one of the first hydropeaking retention basins in Switzerland.

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