Building new power plants under continuous exploitation of neighboring hydropower schemes - planning and construction challenges of the "Tandem" enhancement project in the Central Alps of Switzerland

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Introduction

In the upper Aare River basin, Switzerland, the two power plants Innertkirchen 1 and Handeck 2, are operational since more than sixty years. In the framework of an upgrading program called *KWOplus*, a large number of technical, economic and ecological improvements to the two schemes are actually under realization. With the main goal of reducing friction losses, increasing capacity and minimizing hydropeaking in the downstream river reach, the system enhancements comprise the construction of parallel pressure tunnels and steel-lined pressure shafts, new valve chambers, surge chambers and power houses as well as a compensation basin at the downstream end of the exploited catchment. These numerous civil engineering works take place in a high Alpine environment, where road accesses are restricted during up to six months per year due to meteorological conditions and avalanches. The new hydraulic systems are located only some 20 to 70 m away from existing hydropower plants and are realized almost entirely under exploitation of the latters. The coupling between the new and existing systems has to be planned and executed carefully, as new construction components are to be completed and connected to the existing system. These works will take place during three months, when the plant owner proceeds to the only reservoir drawdown in five years of construction.

The paper describes the enhancement project and emphasizes on the planning and construction challenges under the given site conditions in a high Alpine catchment on one hand and the almost continuous exploitation of several existing and neighboring power plants on the other hand. Complex design requirements, vibration monitoring during the blasting works, the coupling processes of hydraulic systems, measures to cope with hydraulic transients as well as the implementation of a hydropeaking mitigation measure are presented and discussed.

1. Project background

Since the early 20th century, a hydropower scheme of nine power houses and several reservoirs and intakes has been constructed in the upper Aare River basin located upstream of Lake Brienz in the center of the Swiss Alps. The water from the partially glaciered catchment of a surface area of 554 km^2 flows through the artificial reservoirs of Oberaar, Grimsel, Räterichsboden and Handeck and is returned to the Aare River in Innertkirchen. Today, about 60% of the catchment area is utilized by the Kraftwerke Oberhasli AG (KWO). The 26 turbines in all the power plants owned by KWO have a total installed capacity of 1,125 MW and generate around 2,350 GWh of electricity annually, corresponding to approximately 7% of the Swiss hydropower electricity output.

In the framework of an upgrading program for the entire scheme, called *KWOplus*, a large number of technical, economic and ecological improvements are actually under realization. Two existing high head hydropower plants (HPP), the Innertkirchen 1 (INN1) and Handeck 2 (HA2) HPPs, are enhanced within the *KWOplus* program.

1.1 Existing hydropower schemes

The INN1 and HA2 HPPs are operational since 1942 and 1950, respectively. The upstream reservoir of the HA2 HPP, Lake Räterichsboden, provides some 25 Mio. m^3 of storage volume with a maximum exploitation level at 1,767.00 m a.s.l. From the intake structure, water flows through a pressure tunnel to the Handeckfluh surge tank and from there through a steel-lined pressure shaft to the underground power house, located some 460 m below (Fig. 1). There, four Pelton turbines with an installed capacity of 136 MW contribute to power generation. Since the late 1970s, the pumped-storage plant Handeck 3 is connected to the same pressure shaft but can be disconnected to operate water from a side valley of the Aare River. The tailrace tunnel of the HA2 power house leads into a compensation basin and a system of storage tunnels forming the upper reservoir for the next stage, the INN1 HPP.

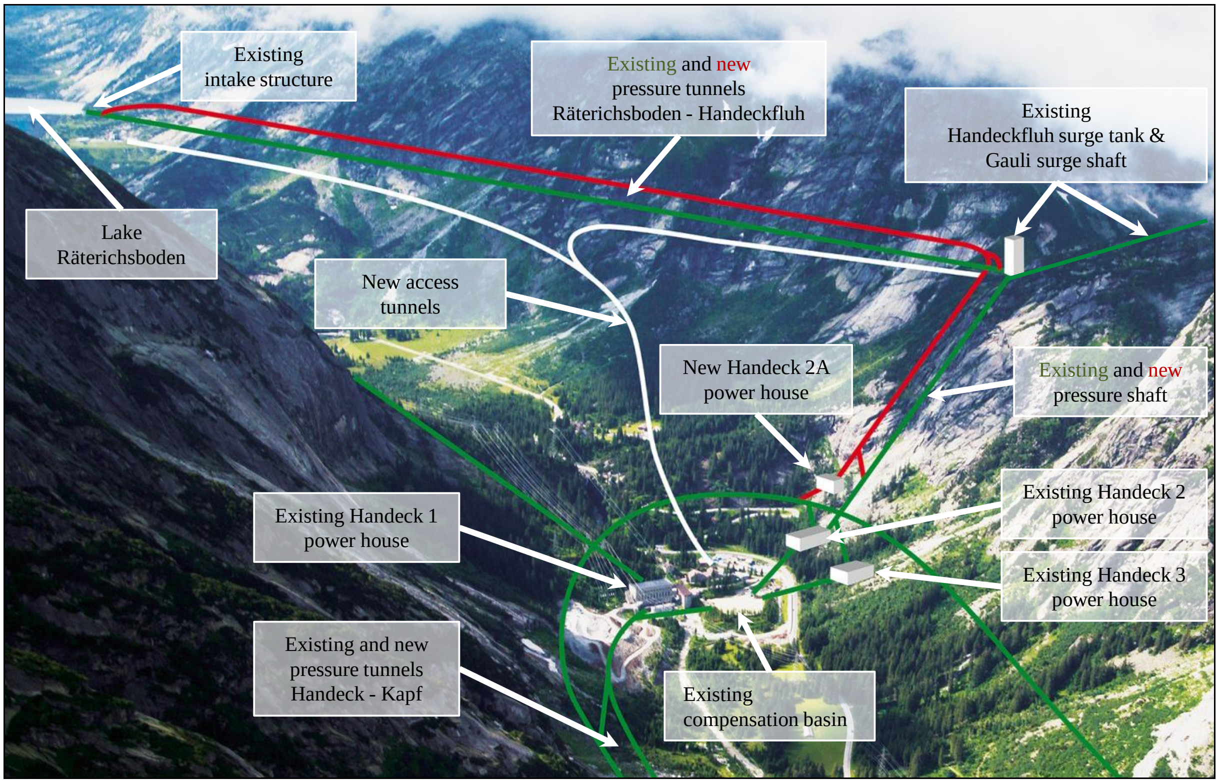


Fig. 1. Overview of the Handeck 2 enhancement project (--- existing and --- new elements)

From the Handeck compensation basin at 1,301.74 m a.s.l., water is guided through a pressure tunnel to the Kapf surge chamber and then flows down a steel-lined pressure shaft toward the INN1 underground power house. Five Pelton turbines with an installed capacity of 255 MW are exploiting the hydraulic head of maximum 672 m. Downstream of the village of Innertkirchen, the tailrace tunnel releases the water back into the Aare River. Figure 2 illustrates the main elements of the existing INN1 HPP and the enhanced scheme INN1E.

1.2 *"Tandem"* enhancement project

In the framework of the upgrading programme *KWOplus*, the so called *Tandem* project comprises several system enhancements for both the INN1 and HA2 HPP. Together with increasing the design discharge capacity of the existing plants, the enhancement project aimed at both, a reduction of friction losses by reducing flow velocities and at a higher operational flexibility of the two plants, respectively. The gain in energy production due to reduced head losses will be 70 GWh per year. By installing one new turbine unit in each of the two systems, the overall installed capacity will increase by 240 MW. In the following, the specific enhancements included in the *Tandem* project are presented for the two HPPs.

The Handeck 2A enhancement project (HA2A) includes a 3,365 m long headrace pressure tunnel excavated parallel to the existing pressure tunnel and connected to the existing intake structure. After some 700 m, the first new valve chamber Gerstenegg is excavated to allow closing a part of the headrace system in case of future revision works. Before joining a second new valve chamber at Handeckfluh upstream of the new pressure shaft, the new pressure tunnel is connected to the existing waterway, including the Handeckfluh surge tank. The new parallel steel-lined pressure shaft leads the water to the new HA2A cavern power house. The Pelton turbine in this cavern will provide an installed capacity of 90 MW. A tailrace tunnel from the plant will guide the water back into the tailrace channel of the existing scheme.

The Innertkirchen 1E/S enhancement project (INN1E/S) comprises a second parallel headrace pressure tunnel, leading toward the Kapf surge chamber. The volume of the latter is increased by the construction of a new chamber connected to the existing system. A new steel-lined pressure shaft parallel to the existing shaft connects the extended surge chamber to the new underground INN1E power house. The additional capacity provided by the Pelton turbine will be 150 MW. The new tailrace tunnel will be connected to the existing one which will be closed by a bulkhead gate at its downstream end. Thus, the released water of the entire enhanced scheme will flow through the new tailrace tunnel into a new compensation basin and from there back into the Aare River.

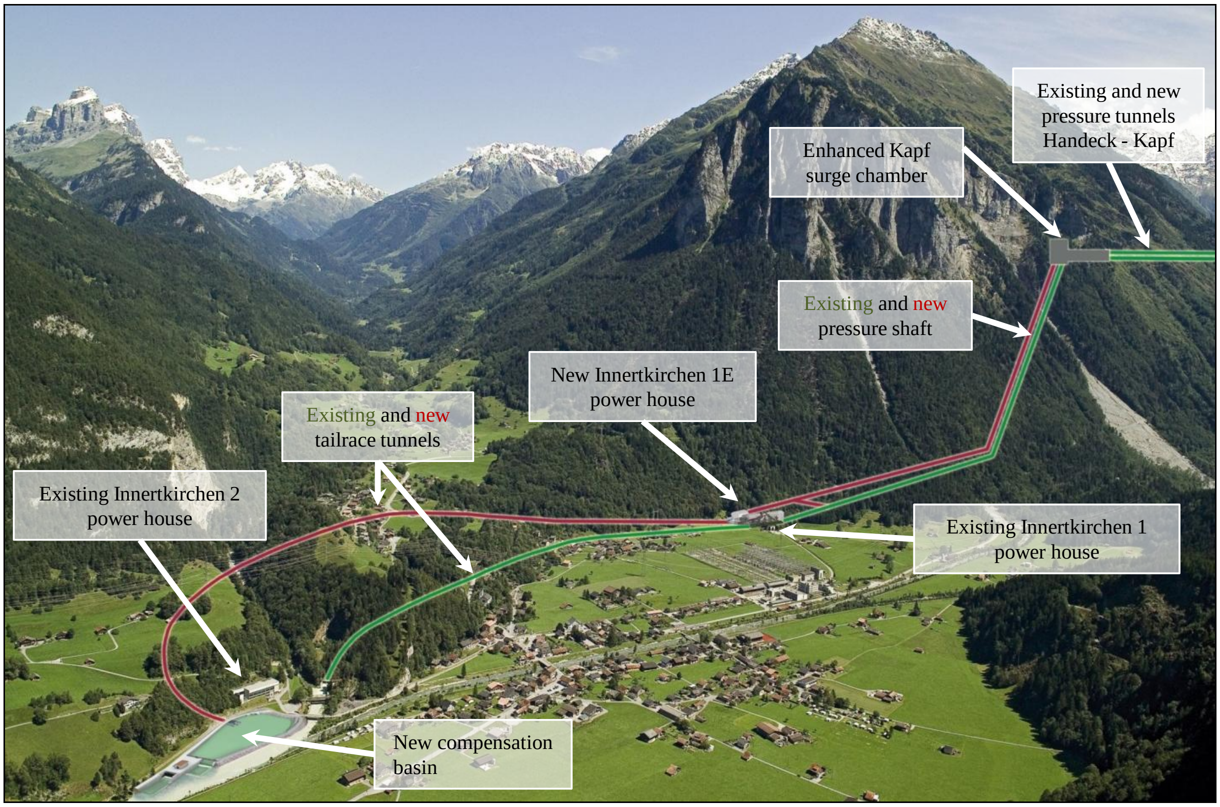


Fig. 2. Overview of the Innertkirchen 1 enhancement project (--- existing and --- new elements)

Today, the main tunneling and blasting works of the INN1E project are completed. In the power house, the new turbine housing and the annular piping have been installed and the concrete works are ongoing while in the pressure shaft, steel-lining and backfilling works are going to be completed in October 2014. As for the HA2A project, blasting works are almost completed; the cut-through of the headrace pressure tunnel will take place in October 2014. The turbine housing has been mounted in July 2014 and the annular piping is actually welded together. The steel-lining and backfilling process started in February 2014, up to today some 350 m have been completed. In parallel, structural works in the new valve chambers are continuing.

2 Meeting restrictive constraints in time and space

The new waterways, surge chambers and power houses are built over some five years from 2011 to spring 2016. In addition to an already very tight schedule, complex constraints had to be taken into account regarding the location of the construction site in a high Alpine environment on one hand, and the proximity to other exploited hydropower systems on the other hand. Thus, high attention was and is paid to the optimization and flexibility of the building programs since the very early planning stage as well as during the construction phase.

2.1 High Alpine construction site

With an annual average temperature around 0°C and lowest values of down to -20°C in winter, the upper Aare catchment is a region of extreme meteorological conditions. Many of the side valleys are very steep, baring the danger of avalanches, especially in the period from January to April. During summer months, the region is of high touristic attraction and the main access roads are consequently occupied by recreational traffic which should not be affected by the construction works.

The Kapf construction site could only be accessed by a ropeway for material transport and a cable car for the workmen. All construction sites upstream of the Handeck power houses are impassable for outdoor traffic during six to seven months per year. Two of three possible deposition areas are located in zones regularly affected by avalanches and thus also susceptible to temporal exploitation interruptions. Consequently, between 2011 and 2013, more than 6 km of access tunnels were excavated applying the conventional mining method prior to the construction of the actual hydraulic tunnels and caverns. These 6.0 m high and 4.8 m wide tunnels lead from the outdoor area close to the existing HA2 power house to the two new valve chambers Gerstenegg and Handeckfluh, as well as toward the future power house. They represent the "lifeline" of the HA2A construction site, as all mucking transports proceed through and the entire ventilation for mining gas evacuation and fresh air is installed in the tunnel ridge. The mucking concept was optimized by the constructor to face the accessibility constraints of the deposition sites. At the same time, the pavement of the tunnel had to be designed to support heavy traffic and executed at very high quality.

2.2 Exploitation constraints

Both enhancement schemes are located at some 20 to 70 m away from existing power plants. The latter are almost constantly exploited by the plant owner during the realization of the enhancement works. The only drawdown of the Räterichsboden reservoir, after which the existing systems can be emptied and the foreseen connections between the new and the existing waterways, surge chambers and caverns can be established, will take place from November 2014 to February 2015. Before and after this period, drilling, blasting and all other civil engineering works are carried out in the vicinity of water filled conduits and running turbines.

Since all excavation works are carried out by drill and blast methods the impact of excavation on continuing exploitation were investigated and monitored in detail. Both, expected and admissible vibration amplitudes were evaluated and blasting restrictions were defined in the tender documents. During construction a monitoring system measuring vibrations at crucial points of the existing systems was installed, with real-time data transfer to the constructors in order to provide them the latest results immediately after a blasting action or during the drilling by a tunnel boring machine (Billeter et al. 2014).

The future system will be operated within the same exploitation water levels as today's scheme and the intake structure in Lake Räterichsboden remains unchanged but evacuates higher discharges from the reservoir. Calculations revealed that air will be entrained at the intake structure at low reservoir levels and maximum turbine discharge. To avoid air transport into the pressurized system or even toward the turbine, a flow straightener as well as three deaerating chambers with a drilled connection to the free surface have been conceived. They will allow accumulation and evacuation of entrained air right after the intake structure as well as in the new and existing pressure tunnel some 300 m downstream of the intake.

2.3 Real-time planning flexibility

For its actual and future hydropower enhancement projects, the KWO aims a dynamic project management from the early planning stages on, but also during the construction process (Biasutti and Fischlin 2013). Thus, conceptual and technical solutions are to be optimized in order to keep them simple and practicable but also prospective for future adaptations. The best solution is very often the result of a close dialogue between the client, the planning engineers and the executing constructor.

After the assignment of the construction works for example, the tunnel sections as well as the longitudinal profile of the entire HA2A waterway had to be changed substantially, as the constructor proposed excavation by conventional mining and the Alimak method instead of a tunnel boring machine. The resulting optimizations led to a change of slope direction of the pressure tunnel, the displacement of the Handeckfluh valve chamber at a lower altitude and a sub-division of the steel-lined shaft into two parts of different slopes.

In the entire *Tandem* enhancement project and according to the geological site conditions, very cost-effective solutions could be adopted regarding a minimal casing of both access and pressure tunnels as well as the shotcreting construction of the power house caverns. Such, the future power houses will neither comprise a secondary concrete ceiling shell nor fair faced brick walls. In tunnels with low future circulation or utilization, the construction inverts will be used as final pavement. However, the structural systems and the hydraulic concepts of the two schemes are conceived to allow future adaptations and above all guarantee a high flexibility in the plant operation.

3 Specific planning and construction challenges

The given constraints require efficient methods as well as high flexibility from all contributors, i.e. plant owner, constructor and planner. In the following, three specific planning and construction challenges related to the *Tandem* enhancement project but considered to present a general interest for other hydropower projects are presented.

3.1 Pressure conduits and hydraulic transients

When refurbishing and extending an existing high head hydropower plant with the purpose to increase power and energy production, design discharge must be increased as well. Therefore, one of the key questions is whether and how the existing hydraulic system has to be extended. The hydraulic system of Alpine power schemes typically consists of an intake structure, a headrace tunnel, a surge tank, a penstock, a tailrace tunnel and an outlet structure. Since the major part of the head loss in the hydraulic system (excluding hydraulic machinery) is produced in the pressure conduits (headrace tunnels and/or penstock) it often proves to be profitable to enhance these conduits for instance by adding a supplementary headrace tunnel and/or an additional penstock.

The extension of both inlet and outlet structures as well as surge tanks (all of them producing discrete i.e. local pressure losses), however, is often (a) technically difficult to realize and (b) economically critical since construction usually interferes with the operation of the existing plant. The extension of HA2 and INN1 HPPs includes additional headrace tunnels and pressure shafts for both plants. Consequently, a crucial technical aspect was whether and how the existing relatively complex surge tanks might be integrated in the new hydraulic system with only minor adaptions or whether an additional surge tank has to be planned. With regard to a most flexible operation of the extended power the surge tank is of utmost importance to control hydraulic transients and to guarantee save and stable plant operation. Therefore, detailed theoretical and numerical investigations were required. For design of the surge tank integration and/or extension extended transient hydraulic computations were carried out. Theoretical considerations and the computations yielded the following main results:

(I) If the extension of the headrace pressure conduits leads to a significant reduction of the head loss (although the total discharge is increased), down-surges will not be critical and no alterations in the lower part of the surge tank will be necessary.

(II) The head for stationary operation in the surge tank, however, will increase by reducing pressure losses. Therefore, additional surge tank volume might be needed in the upper part of the surge tank structure.

In Figure 3 two typical examples of transient computation results are demonstrated for the Handeckfluh surge tank (Fig. 3a) and the Kapf surge chamber (Fig. 3b). Time series of discharge and pressure heads (water levels) of the surge tank are compared for the existing and the extended hydraulic systems.

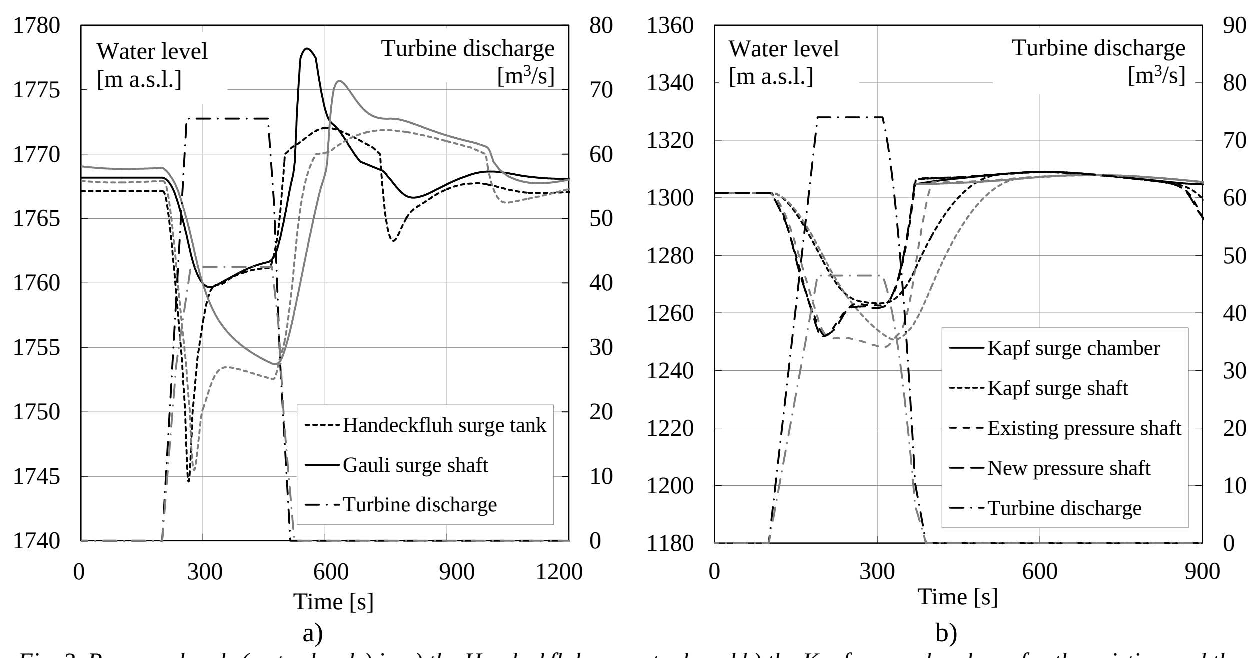


Fig. 3. Pressure heads (water levels) in a) the Handeckfluh surge tank and b) the Kapf surge chambers, for the existing and the enhanced HPP configurations

For the HA2 HPP it was possible to connect the additional and the existing pressure conduits such that no extension of the surge tank was necessary. Hydraulic connections of the two parallel conduits at both the surge tank level and a position immediately upstream of the turbine valve proved to be most efficient to damp out surge oscillations under varying operation conditions.

For the INN1 HPP the same concept of connecting the new and the existing headrace pressure system was applied, allowing to minimize the extensions in the lower part of the surge chamber. To control the up-surge under emergency shut-down conditions however, an additional upper surge chamber was necessary. To reduce conflicts with the existing surge chamber and to guarantee plant operation during construction of the new surge chamber, a design as shown in Figure 4 was chosen. Careful excavation planning including restrictive conditions for blasting made it possible to construct the new chamber without interrupting operation.

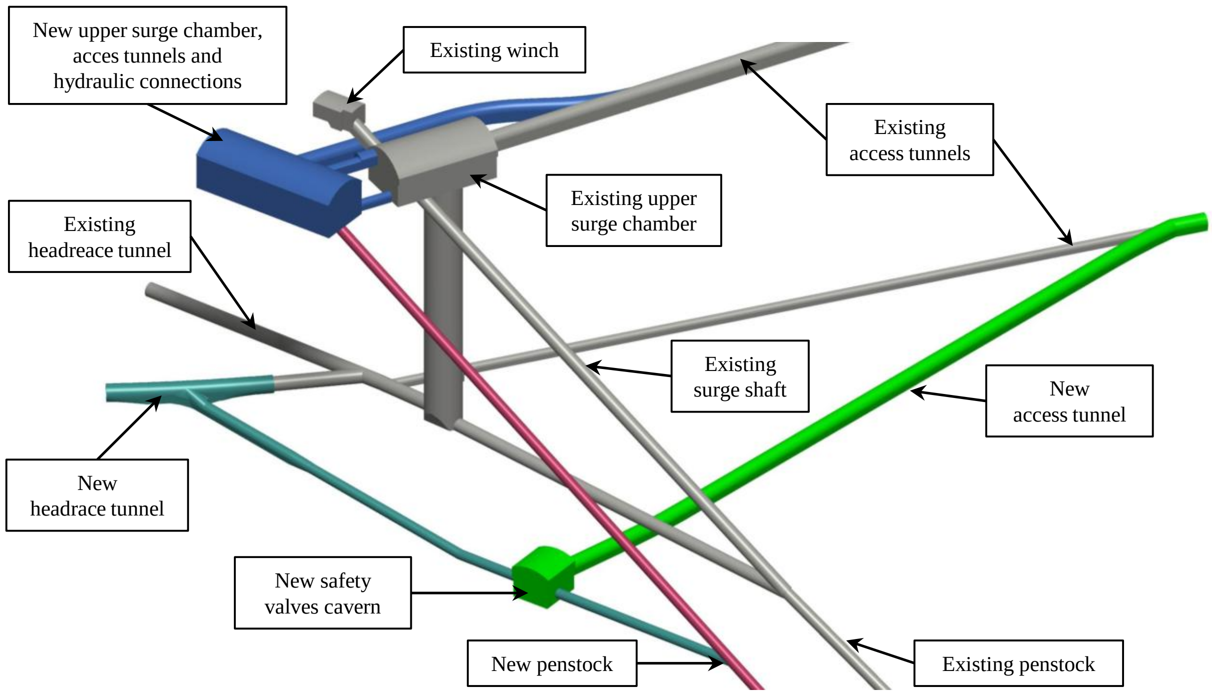


Fig. 4. 3D-view of the surge tank system of the enhanced Innertkirchen 1 power plant

3.2 Coupling processes of hydraulic systems

Connections between the existing and the new schemes are to be realized during one single time period of sixteen weeks from mid-November 2014 to end of February 2015, when the plant operator proceeds to a drawdown of the Räterichsboden reservoir. This construction phase requires detailed and optimized planning and preparation works from both civil engineering companies and constructors.

The new HA2A pressure tunnel will be connected to the existing intake structure and to the Handeckfluh surge tank. At Kapf, the new INN1S surge chamber has to be coupled to the existing chamber by several connecting tunnels. In both schemes, the parallel pressure shafts are to be coupled by a steel-lined connection and the new tailrace tunnels will be finalized to join the existing ones. In addition, an emergency tunnel between the two Handeck 2 underground power houses remains to be established.

The existing plants will again operate under normal conditions after this drawdown period while the new systems will still be partially disconnected from the water-filled system. Steel shells installed before the re-filling process in February 2015 assure that the future waterway can be completed under dry conditions.

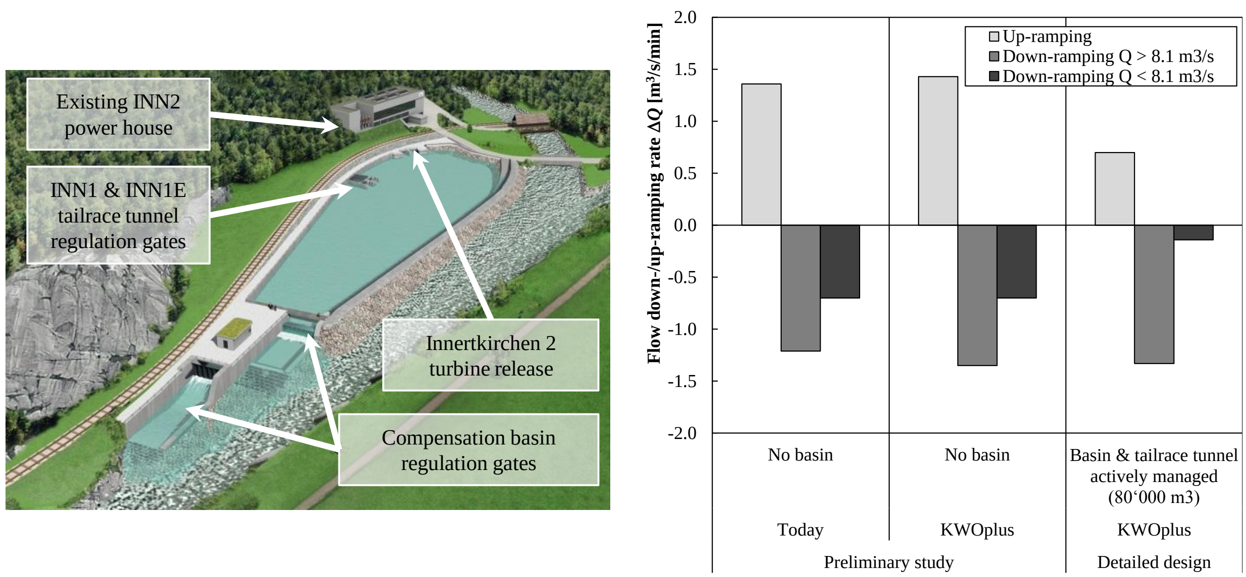
3.3 Reduction of downstream impact of hydropower operation

Sudden opening and closing operations of the turbines produce highly unsteady flow in the river downstream of hydropower plants (Moog 1993). This so-called hydropeaking is the major hydrological alteration in Alpine regions and disturb the natural discharge regime, a key factor in ecological quality and the natural abiotic structure of ecosystems. In Switzerland, Parliament adopted the Law on Water Protection in 2009 (in force since January 2011) to improve the quality of Swiss waters, including hydropeaking mitigation.

Therefore, a hydropeaking mitigation measure has been planned in the framework of the INN1E enhancement project. To reduce the negative impact of the foreseen increase of the turbine discharge, a compensation volume has to be implemented at the downstream end of the plant (Fig. 5a). Preliminary hydrological simulations showed, that a volume between 50,000 and 100,000 m^3 would lead to much better ecological conditions in the future, not only compared to the future situation without mitigation measures, but also compared to toady's situation (Bieri et al. 2014). Based on a cost-benefit-analysis, an expert panel of environmental specialists, engineers, representatives of cantonal and federal authorities as well as the plant owner selected a volume of 80,000 m^3 as the most convenient compromise, acceptable for all of the involved partners.

As the on-site conditions do not allow the construction of a surface basin of this required volume, the new 2.1 km-long tailrace tunnel between the INN1E power house 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. Taking into account system and operation constraints given by the plant operator a regulation algorithm calculates the discharge Q_{out} which has to be released during the next fifteen minutes, based on instantaneous and predicted turbine discharges of the INN1, INN1E and INN2 HPPs and the actual available storage volume in the system. System safety, maximum up- and down-ramping rates, operation flexibility and desired up- and down-ramping rates are prioritized in the algorithm to best manage the retention volume.

The regulation performance is evaluated with the 95%-percentile of daily maximum values. Results reveal that even under relatively strict operation and safety/reliability constraints, flow up-ramping rates can be reduced from 1.36 m^3/s/min (today) and 1.43 m^3/s/min (*KWOplus*) to 0.70 m^3/s/min under optimum regulation parameters. The down-ramping rates are decreased to -1.33 m^3/s/min for high discharges and to -0.14 m^3/s/min for discharges lower than 8.1 m^3/s (Fig. 5b). The tailrace 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.



a) b)

Fig. 5. a) Overview of the main elements of the compensation basin, b) 95%-percentile of flow up- and down-ramping rates immediately downstream of the outlet of the compensation basin for winter conditions from 2009 to 2012 for today's and the enhanced INN1 HPP without retention volume (preliminary study) and with active volume management for both basin and tailrace tunnel (detailed design)

4 Conclusions and recommendations

Relevant aspects of the planning process for a vast enhancement project at existing hydraulic systems and power plants were presented. The construction of the additional conduits, caverns and installation takes place in close vicinity to the existing structures and to the plant under continuing exploitation. Key questions to be solved for successful realization were among others:

(I) Minimization of the extent of new structures (conduits, caverns, installations, machinery) by optimized integration of the existing hydraulic systems and the existing plants. This included both constructional and operational aspects.

(II) Hydraulic aspects of the plant enhancement and the coupling of the new and the existing hydraulic systems including head loss optimization, hydraulic transients and hydropeaking mitigation measures with regard to environmental requirements.

(III) Construction process planning and monitoring with regard of continuing exploitation of the existing plants and minimizing production losses when coupling the systems.

The presented *Tandem* enhancement project leads to a considerable reduction of friction losses, not only in the new tunnels and shafts, but also in the existing waterways. Instead of building bigger hydraulic structures and waterways, the construction of a parallel system allows for the integration of existing structures which are in good conditions and helps to keep the enhancement projects cost efficient.

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