Task 2.2

Title

Infrastructure adaption

Projects (presented on the following pages)

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Menacing Waves: Enhancing the Risk Assessment for Impulse Waves in Reservoirs
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Kraftwerk Juchli - Exploitation of Juchli waterfall with a small hydropower plant
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Impacts of Future Market Conditions on Hydropower Storage Operations
Alternative: Work Package 5
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Fine sediment release from reservoirs through venting of turbidity currents
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Potential for future hydropower plants (HPPs) in Switzerland
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Fine sediment management at hydropower schemes considering turbine erosion
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Blocking probability at spillway inlets under driftwood impact
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Utilisation optimale du potentiel hydroélectrique d’un bassin versant alpin: le barrage de Khudoni en Géorgie
M. Jordan, S. Venuleo, P. Manso, A. Schleiss

Online prediction tool for hydropower energy (Opt-HE)
F. Jordan, G. Artigue, K. Cros, C. Loetscher, O. Etter, A. Schleiss

Operation changes of a complex hydropower system over decades
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J. P. Matos, P. Manso, B. Schaefli, A. Schleiss

Evaluation du potentiel d'augmentation du stockage saisonnier d'énergie en Suisse en vue des changements climatiques
B. Monay, J. Dujardin, P. Manso, M. Zappa, A. Schleiss

Confortement d'un barrage poids en maçonnerie présentant une légère courbure en plan : le barrage de Cenne-Monestiés
A. Nicolle, S. Chamoun, P. A. Manso, A. J. Schleiss

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M. Noseda, A. J. Schleiss, M. Pfister, I. Stojnic

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Floating Debris at Dam Spillways: Hazard assessment and Engineering Measures
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Assessment of the cavitation risk for throttled surge tanks

Nicolas J. Adam, Giovanni De Cesare & Anton J. Schleiss
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Introduction

The Swiss confederation aims to phase out nuclear power production with the Energy Strategy 2050. Hydroelectricity has supplied approximatively 60% of the domestic electricity production for 40 years (SFOE, 2016). High head power plants (Figure 1), which represents 60% of Swiss hydroelectricity, may be refurbished in order to increase their flexibility or their peak-hours generation to supply the versatility of the new means of generation, e.g. wind or solar generation.

Surge tanks (Figure 1) are hydraulic devices, part of a high head power plant. They protect the pressure tunnel from the water hammer, which are produced by the change of discharge in the waterway system, and damp the mass oscillations. An increase of the generation capacity, either by heighten the dam or increase the discharge capacity, leads generally to a worsening of the mass oscillations. Throttled surge tanks improve the damping of mass oscillations. It allows optimizing the behavior of an existing surge tank. There are different types of throttle such as orifice, rack or bar screen and vortex throttle. This study focuses on chamfered orifices as shown in Figure 2.

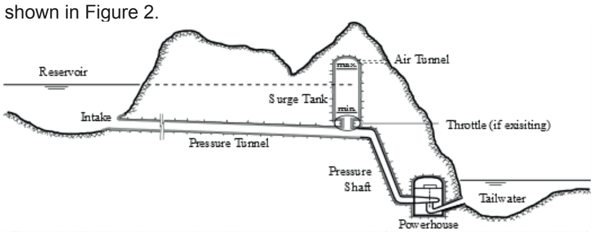

Figure 1 : High head power plant with upstream surge tank (typical scheme in alpine valleys)

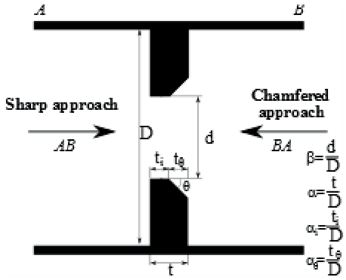

Figure 2 : Chamfered orifices and main geometrical parameters

Cavitation risk with incipient cavitation number σ_i

The incipient cavitation number σ_i, given by Eq. (1),characterizes the cavitation within the throttle. In this cavitation stage, there is no damage to the structures and the influence of the cavitation is very low on the flow characteristics, e.g. head losses produced by the throttle.

$$\sigma_i = \frac{p_u - p_{vg}}{p_u - p_d} \tag{1}$$

Ferrarese et al. (2015) proposed a new method for predicting σ_i. The pressures involved in the evaluation of σ_i are based on single phase CFD simulations. They showed that the value of σ_i is well predicted when the minimum pressure p_{min} in the pipe is equal to the vapour pressure p_{vg} as given by Eq.(2).

$$\sigma_i = \frac{p_u - p_{\min}}{p_u - p_d} \tag{2}$$

Figure 3 gives the predicted values of for an orifice as a function of the contraction ratio *β* and the inner thickness ratio *α_i* for the sharp approach flow.

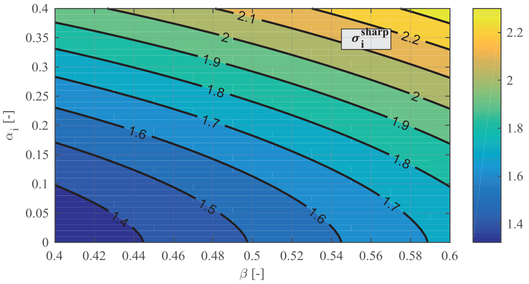

Figure 3 : Incipient cavitation number for the sharp approach flow as a function of β and α_i

Cavitation risk in surge tank orifices

By assuming a quasi-steady flow in the mass oscillations between the surge tank and the reservoir and that cavitation does not influence the head losses and the other flow characteristics, the limit between the zone without and with a risk of cavitation for down-surge (Eq.(3)) and for up-surge (Eq.(4)) as:

$$H_{ST} = \sigma_i \left[\frac{8\beta^4}{g\pi^2 d^4} k - \kappa_Q \right] Q^2 + p_{vg} \tag{3}$$

$$H_{ST} = \left(\sigma_i - 1\right) \left[\frac{8\beta^4}{g\pi^2 d^4} k - \kappa_Q \right] Q^2 + p_{vg} \tag{4}$$

Where k is the head loss coefficient, d the inner thickness ratio, κ_Q is a correction factor due to the difference of kinetic energy between the pressure tunnel and the surge tank and Q the discharge flowing into or out of the surge tank.

These two limits of the cavitation risk are applied to an existing throttled surge tank (Adam et al.,2017) subjected to an emergency closure (Figure 4). Two cavitation risks are highlighted but with relative small durations (17s for the up-surge and 80 s for the down-surge). However, this cavitation is still limited.

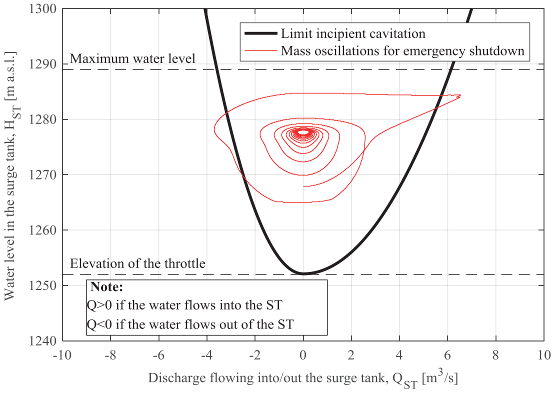

Figure 4 : The cavitation risk (water at 5°C) for the Gondo surge tank (Adam et al.2017) subjected to an emergency shutdown leading to converging mass oscillations

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Menacing Waves: Enhancing the Risk Assessment for Impulse Waves in Reservoirs

Claudia Beck, Lukas Schmocker, Helge Fuchs, Frederic Evers, Robert Boes - VAW, ETHZ; Axel Volkwein - WSL

Motivation

Impulse waves, generated by avalanches, ice- or rockfalls, may seriously impair the reservoir of a hydropower plant. In some cases they even overtop or damage the dam and trigger hazardous flood waves (Fig. 1). Examining their potential impact is therefore an inevitable part of a comprehensive hazard assessment for hydropower reservoirs in alpine areas.

Fig 1: Impulse wave generation at Grindelwald Glacier Lake (Photo: Hans-Ruedi Burgener)

The impulse wave features in reservoirs and the possibility of dam overtopping can be evaluated by a computational procedure established at VAW (Heller et al. 2009). Recent research on spatial wave propagation (Evers and Hager 2016)will complete this hazard assessment tool. For a proper validation of the procedures based on analytical and semi-empirical data from small-scale models, reliable field data on impulse waves or large-scale experiments are still missing. New field data shall therefore be collected by means of a large-scale field test. An innovative test-setup is planned at Grimselsee, where artificially generated impulse waves will be studied in prototype. For the impulse waves generation, a rail wagon will slide on guiding rails at high speed into the reservoir.

Laboratory tests

Within the CTI project FlexSTOR, both laboratory tests at VAW and prototype field tests at Grimselsee are carried out to investigate the impulse wave generation and propagation. A rail wagon will be used to represent gravitationally-driven landslides. The small-scale model tests were carried out with a model scale of 1:50 (Fig. 2). A rail wagon was manually accelerated on an inclined ramp. The wave heights were measured at three locations along the wave propagation path using ultrasonic distance sensors. The tests showed that for a targeted slide mass of 10 tons and an impact velocity of around 25 m/s, the maximum resulting wave height in prototype is ≈1 m.

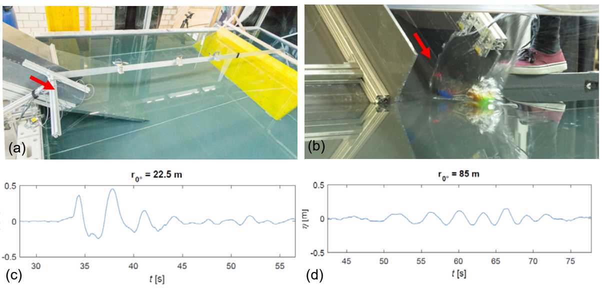

Fig 2: (a) Part of Grimselsee in VAW Laboratory at 1:50 scale; (b) Impact of railway wagon and wave generation in laboratory; Water surface displacement *η* at a propagation distance of (c) 22.5 m and (d) 85 m.

Field tests

The prototype tests planned at the KWO reservoir Grimselsee offer a unique chance to collect rare and valuable field data on impulse wave generation and propagation under systematic and controlled conditions. An optimum location for the field test is Grimselsee, as there is already a gate rail available where a rail wagon can be slid into the reservoir (Figure 3 and 4). The rail has an inclination of 48° and the load capacity of the rail wagon is around 5-10 tons. The field tests are scheduled for summer 2018, when the reservoir will be at a low level and the rail wagon may be accelerated to about 25 m/s before impact.

Fig 3: Lowered Grimselsee in 2006 with Spitallamm dam on the left and existing railway. (Photo: KWO)

Fig 4: Rail wagon with a weight of approx. 6 tons. Additional weight will be added with steel plates and water tanks. The wagon front will be equipped with a vertical steel plate to increase momentum transfer.

Acknowledgement

This project is financially supported by the Swiss Commission for Technology and Innovation (CTI) with the industrial partner Kraftwerke Oberhasli (KWO). It is part of the FlexSTOR project which stands for “Solutions for flexible operation of storage hydropower plants in changing environment and market conditions” and is embedded in the Swiss Competence Centre for Energy Research - Supply of Energy (SCCER-SoE) framework. .

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Kraftwerk Juchli
Exploitation of Juchli waterfall with a small hydropower plant

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Introduction

The small hydropower plant project Kraftwerk Juchli, proposed by Kraftwerke Oberhasli AG (KWO), would allow using the potential created by the construction in the 1950's of the underground gallery to transfer the water collected from the river Bächlibach to the lake of Grimsel.

The project is situated on the territory of the municipality of Guttannen in the canton of Bern, near the pass of Grimsel (see Figure 1).

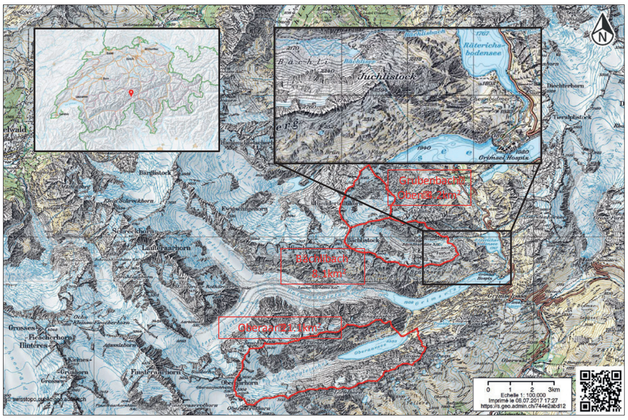

Figure 1. Geographical situation of the Kraftwerk Juchli project and the watersheds studied with the RS Minerve software (geodata © swisstopo).

The adduction gallery concerned by this project is represented in Figure 1. It allows connecting the Bächli lake with the Aar valley at the level of the Grimsel lake by passing under Juchlistock. The tunnel has a total length of 1'348 meters and a slope of 0.75%.

The existing facilities located in the Bächli valley are represented in Figure 2. The area located upstream of the Bächlibach dam is a protected alluvial zone with a national level of importance, forbidding any modification of the environment.

Figure 2. The Bächlibach dam which diverts the water into the Bächli gallery. The water intake is equipped with a trashrack to avoid big stones to enter the gallery. The capacity of the water intake is 7.5 m³/s.

In addition, the former artillery fortress of Grimsel as well as the project of replacing the Spitallamm dam could bring some synergies to the project. Scenarios with or without the extra height of the level of Grimsel lake are to be taken into consideration.

Methods

1. Modelling of the Bächlibach and Grubenbach Oben watersheds on the software RS Minerve. The results of the modeling will supply the discharge data at the exit of the watershed.
2. Study of various alternatives of exploitation of the waters from the Bächli river.
3. The most interesting alternative is chosen for a more thorough study which contains the dimensioning of the hydraulic elements.
4. Study of the project's impact on the environment.
5. Estimation of the cost for the construction of the small hydropower plant.

Concepts of exploitation and alternatives

- Concept of exploitation : Run-of-river.
- Storage and turbine-and-pump are not practicable because of their impact on the environment.

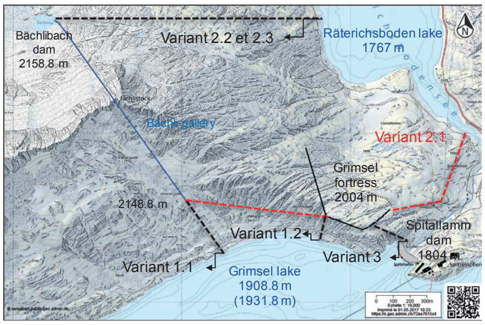

Figure 3. The variants of exploitation for the project Kraftwerk Juchli. The solid lines represent the existent galleries (geodata © swisstopo). Representation of the different existing facilities and their altitude. The maximum elevation of the level of the Grimsel lake is 1908.8 m a.s.l. but a project is in study to raise the level to 1931.8 m a.s.l. The Spitallamm dam is one of the two dams which were built to create the Grimsel reservoir. The Grimsel fortress could be used to install a part of the penstock pipe.

Alternatives

1. Bächlibach – Grimsel lake	Head : 250 m (227 m)
2. Bächlibach – Räterichsboden lake	Head : 390 m
3. Bächlibach – Spitallamm dam	Head : 353 m

From the 6 variants proposed, variant 2.1 (see Figure 3) is chosen as the best one for which all works have been designed.

Pre-project of the small hydropower plant

With a designed discharge of 1.7 m^3/s, 19.1 GWh/year of net power can be produced by means of one Pelton turbine.

Hydraulic structures :

- Efficiency of the sandtrap : 0.2 mm
- Length of the penstock pipe : 1'830 m
    - 1'355 m : polystyrene reinforced with fiberglass (PRV)
    - 475 m : stainless steel
- Turbine Pelton : 2 injectors and a vertical axe of rotation (see Figure 4)

Figure 4. Picture of a Pelton turbine with two injectors from the power plant Le Lauzet in France (Cerec Engineering):

The engine room is installed in the assembly cave of the Grimsel 1 hydropower plant.

Conclusion

- Installed capacity : 5.8 MW
- Investment cost : 12.2 million CHF
    - Civil works : 8 million CHF
    - Hydromechanical equipment : 1 million CHF
    - Other costs (engineer, capital cost, etc.) : 3.2 million CHF

Economic evaluation

Return period : 25 years, till the end of the actual concession.

Interest rate: 3 %

- **Generation cost** : 4.4 cts/kWh

The profitability of the project is guaranteed if it benefits from the compensatory feed-in remuneration (RPC). Without the RPC, the project can be profitable if the electricity selling price is a bit higher than the actual market price. A renewable energy label could ensure a bonus of 1 ct/kWh.

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Impacts of Future Market Conditions on Hydropower Storage Operations

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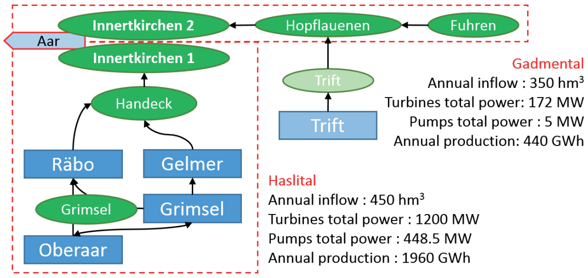
Introduction

In this work developed within the Energy Strategy 2050 frame, we want to assess future hydropower production constraints using numerical simulation tools and several scenarios, both climatic and economic, prepared by partners. Through the specific case study of the KWO system, several alternatives will be explored, including benefits from storage vs run-off-based production.

Case Study : KWO System, Upper Aar river basin



Gadmental
Annual inflow : 350 hm³
Turbines total power: 172 MW
Pumps total power : 5 MW
Annual production: 440 GWh

Haslital
Annual inflow : 450 hm³
Turbines total power : 1200 MW
Pumps total power : 448.5 MW
Annual production : 1960 GWh

Figure 1 : Simplified KWO Scheme with main reservoirs (blue) and power stations (green). Light green and blue show future Trift infrastructures.

Numerical Modelling

Routing System 3, developed by Hydrique Ltd. in Lausanne, is a tool that allows building semi-distributed hydrological models using modules representing different elements and functions of catchments and hydraulic infrastructures. Figure 2 illustrates the global KWO model.

The hydraulic part uses the *Optiprod* module of RS3, to simulate an optimised production based on target curves day-ahead prices, base operation prices, and elasticity coefficients (Figure 3).

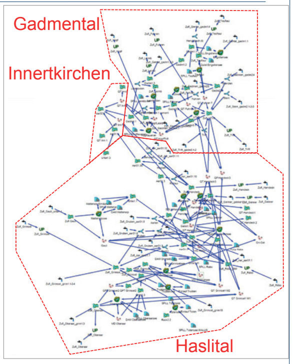
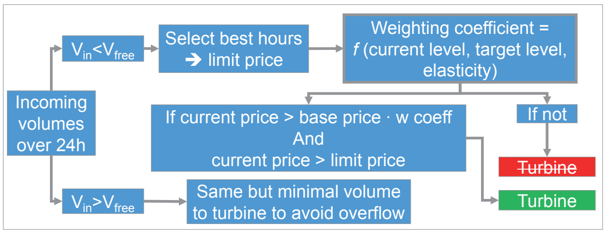


Figure 2 : RS3 full KWO model



Incoming volumes over 24h
$V_{in}<V_{free}$
Select best hours ➔ limit price
Weighting coefficient = *f* (current level, target level, elasticity)
If current price > base price · w coeff And current price > limit price
If not
~~Turbine~~
Turbine
$V_{in}>V_{free}$
Same but minimal volume to turbine to avoid overflow

Figure 3 : 'Optiprod' decision'algorithm (simplified)

Limits :

- Operation constraints (maintenance, long-term contracts, grid balancing) can not be reproduced
- Simulated facilities are not coordinated with each other.

Despite existing limitation, adjusting coefficients allows the simulation of coherent behaviours, leading to an annual production close to reality (according to historical daily flows given by KWO).

Aknowledgments

Thanks are owed to Jan Baumgartner, Marcel Schläppi and the rest of the KWO team. Likewise, we are thankful to Massimiliano Zappa from WSL for his contributions.

Available scenarios

Economic scenarios by FoNEW (*Forschungstelle fur Nachaltige Wasser- und Energieversorgung*), from the *Swissmod* electricity market model. They include a base scenario and variations over three main hypothesis : carbon prices, fuel prices and (non-hydraulic) renewable part in total production. Data provided from 2020 to 2030.

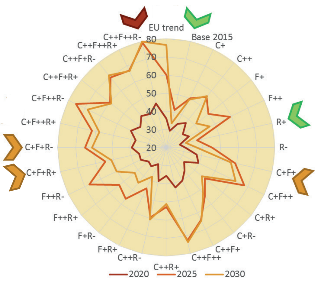


Figure 3 : Economic scenarios (mean prices €/MWh)

Results – economic impacts

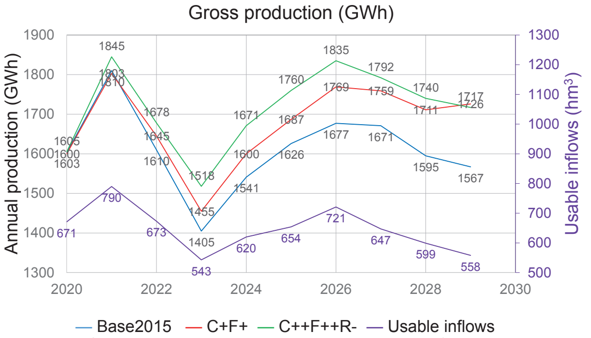


Figure 4 : Simulated annual production and usable inflows predicted by A1B climate scenario (WSL). Simulations for the hydrological year 2015-16 lead to 2050 GWh produced from 841 hm³ available inflows.

Simulated annual production (Figure 4) logically follows variations of inflows (purple). The difference between economic scenarios (only three represented above) comes from the pump-storage station, which activity depends mainly on peak energy prices.

Discussion – improvement opportunities

Benefits of the new Trift dam (collecting and storing about 60% of Gadmental inflows) include 8-10% increase in total production (from the new power station) and a 13-15% rise in revenues (production increase and better operation time thanks to annual storage).

Other ways of improvement :

- Enlarging lake Grimsel (currently too small compared to its inflows, and higher flexibility for future pump-storage operations).
- Turbining water from Mattenalpsee to Räterichsbodensee (currently transferred without production).
- Exploiting unused parts of the watershed (Urbachtal, lower Haslital).

Options with less potential benefits :

- Increasing the capacity of diversions (already capturing more than 95% of total inflows and more than 90% in the future).
- Turbining from small lakes (only small volumes available).

Conclusion

Using Routing System 3 modelling tools and several climatic and economic scenarios, future constraints were simulated and a set of possible improvements explored. In particular, the benefits from annual storage vs run-off operations were shown.

The complexity of the KWO case study renders precise simulation difficult and a deeper analysis may require the development of new tools. However, the method can easily be applied to other infrastructures, existing or planned, or even to a generic installation, representative on a larger regional or national scale.

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Fine sediment release from reservoirs through venting of turbidity currents

Sabine Chamoun, Giovanni De Cesare, Anton J. Schleiss

Introduction

Dams are essential structures in modern societies. The reservoirs created by such structures provide crucial services such as irrigation, hydropower, flood control, and water supply. Nevertheless, processes such as sedimentation are hindering the sustainability of reservoirs, shortening their lifetime and reducing their efficiency. One of the main sources of fine sediments in reservoirs are turbidity currents, created by density differences due to their high sediment concentrations. Turbidity currents can flow along the reservoir and reach the dam site. Therefore, the sediments they suspend can block low-level outlets/intakes and reduce the capacity of the reservoir. Dealing with such currents can be done by venting it through low-level hydraulic structures. In the present work, different parameters related to venting were investigated. Their effect on the sediment release efficiency were studied using experimental and numerical approaches. The influence of outflow discharge using the horizontal bed is presented hereafter. Both experimental and numerical results are shown and compared.

Methods

The approach used in this research was mainly experimental. A long and narrow flume was used at the Laboratory of Hydraulic Constructions (LCH). It simulates the reservoir in which turbidity currents were triggered. The latter flew along the reservoir until reaching a wall simulating the dam and into which a rectangular orifice, representing the bottom outlet, was placed. An outflow discharge was applied at the outlet when the current reached it. The turbidity current was then vented and evacuated into a downstream basin. Inflow and outflow discharges and concentrations were amongst the main parameters tested. Deposition was also measured in space and time and allowed to reach realistic efficiency values by subtracting deposited sediment masses from inflowing mass when comparing the latter to the outflowing sediment masses. This is done since no retrogressive erosion is involved during venting. These parameters allowed the calculation of the venting efficiency in time, which is used as the main criterion to compare the different scenarios tested using different outflow discharges among others.
Moreover, a numerical model was built based on the geometry of the experimental model. The software ANSYS Inc. was used with the CFX solver. In order to simulate the complex dynamics of turbidity currents including deposition, drag and the sediment's settling velocities, several equations were added to the solver as CEL expressions. The expressions' parameters were then calibrated and the results were validated based on the experimental data. The numerical results served as an extension to the experimental data.

Experimental results and discussion

Numerous reported cases of reservoirs where turbidity currents occur showed that the bed in the close vicinity of the outlet/dam approaches horizontal. In fact, when a turbidity current reaches the dam, unless it is evacuated, it reflects at the dam forming a muddy lake which eventually settles, thus flattening the slope of the thalweg. For this reason, one of the slopes tested is horizontal.

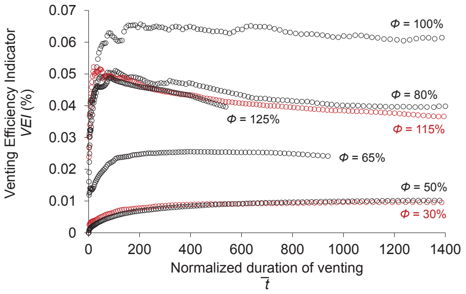

Fig.1: Venting efficiency indicator as a function of the normalized venting duration for different venting degrees tested using the horizontal bed

Seven different venting degrees ϕ, defined as the ratio between the outflow discharge and the turbidity current inflow discharge, were tested starting from 30% up to 125%. The criterion shown in Fig. 1 is the venting efficiency indicator (*VEI*) which considers not only sediment fluxes in and out of the flume during venting, but also the clear water losses induced by venting. Water loss is a particularly important aspect regarding reservoirs used for hydropower generation. It was shown that the venting degree ϕ = 100% induced the least water losses and the highest sediment release. For higher venting degrees, the clear water loss increased thus decreasing the efficiency of venting. More details on the presented experimental results can be found in Chamoun et al. (2017).

Numerical results and discussion

The geometry of the numerical model was based on the experimental model. In order to validate the model, criteria such as the front velocity (Fig. 2), the outflow concentration (and thus the venting efficiency) and velocity profiles from the body of the current were considered.

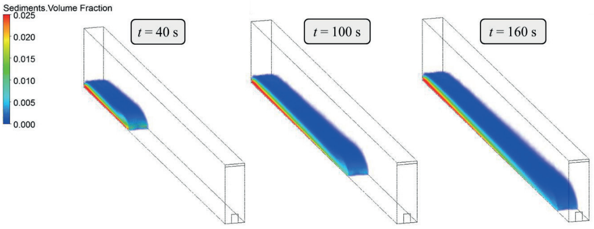

Fig.2: The progress of the turbidity current simulated numerically at different time steps "t" of the simulation.

The Representative venting efficiency *RVE*, which computes the average value of the efficiency calculated once outflow concentrations reach a steady value, is shown in Fig. 2 as a function of venting degree. Contrarily to the *VEI*, the *RVE* only accounts for inflow and outflow sediment masses and does not consider clear water losses. The numerical model allowed testing higher venting degrees than the experimental tests reaching ϕ = 200%. As concluded experimentally, the *RVE* values show that starting ϕ = 100%, there exists a change of trend. The rate of increase of efficiencies is reduced. Therefore, the water losses start increasing when ϕ > 100%. Hence, the venting degree leading to the highest venting efficiencies in the presence of a horizontal bed in the vicinity of the outlet is of 100%.

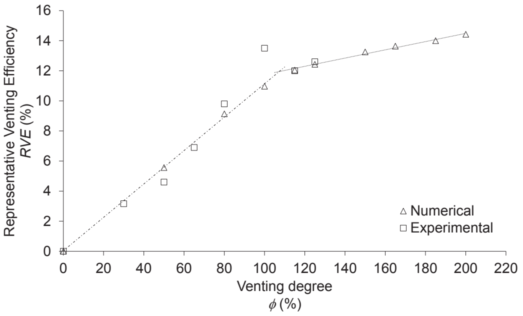

Fig.3: Representative venting efficiency RVE as a function of the venting degree ϕ for a horizontal bed. The trend lines correspond to the numerical data.

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Acknowledgments: This research is funded by Swisselectric Research and the Swiss Committee on Dams.

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Rehabilitation of Isola arch-gravity dam facing an internal swelling reaction

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Motivation of the project

As many other aging Swiss dams, the Isola arch-gravity dam, built in 1960, is facing an internal swelling reaction inducing an adverse stress and strain state. In order to avoid structural issues linked to diffused and uncontrolled cracking, solutions for reducing the effects of concrete swelling on the structure are studied.

Current state of the structure

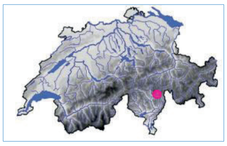

1. Downstream face of the dam

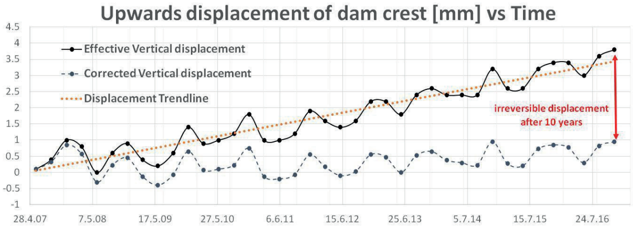

2. Gated Spillway with cracking and brown colouring of concrete due to internal swelling reaction

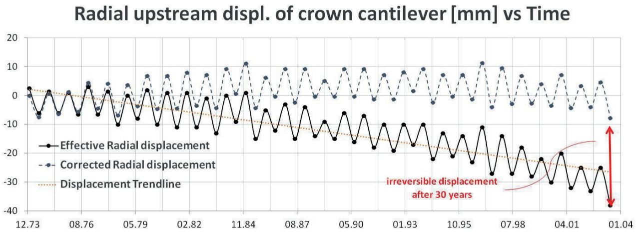

3. Upstream face of the dam with watertight membrane band

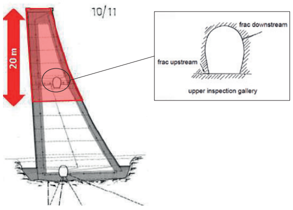
Crown cantilever height	45	m
Arch crown height (Bloc 10)	35	m
Concrete volume	71'000	m3
Maximum base width	22	m
Crest width	5.5	m
Crest length	290	m
Reservoir volume	6.2e6	m3
Lombardi coefficient	11	

Table 1. Dam characteristics

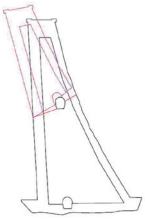

4. Dam location: San Bernardino


Upwards displacement of dam crest [mm] vs Time


Radial upstream displ. of crown cantilever [mm] vs Time

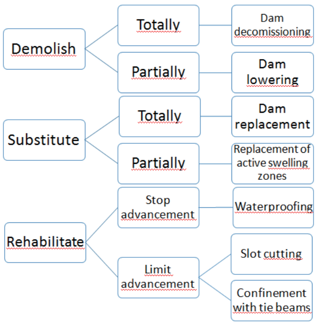


5. Active swelling zone and upper inspection gallery sub-horizontal crack (30°)


6. Possible displacement mechanism deduced from observed cracking

Multiple criteria decision analysis

If no action is taken:
- Cracking will increase
- Local stability may be put at risk
- Water penetration in the dam body may occur.
- Concrete resistance and stiffness will decrease


- Demolish
  - Totally
    - Dam decomissioning
  - Partially
    - Dam lowering
- Substitute
  - Totally
    - Dam replacement
  - Partially
    - Replacement of active swelling zones
- Rehabilitate
  - Stop advancement
    - Waterproofing
  - Limit advancement
    - Slot cutting
    - Confinement with tie beams

<u>The selected solution is the **diamond wire slot cutting** for it is:</u>
- Economical
- Fast
- Sustainable

<u>Parameters to be determined for such an intervention are:</u>
- Number of slots
- Length of slots
- Position of slots
- Width of slots

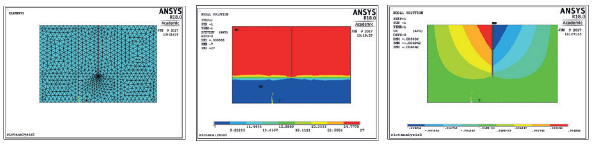
Designing the diamond wire slot cutting intervention

Objective of intervention: elastic recovery of accumulated strain by allowing concrete to expand at slots. A FEA is used to forecast slot closure in order to design intervention.

Main assumptions:
-swelling is homogeneous across affected areas
- chemical expansion modelled by an equivalent thermal expansion

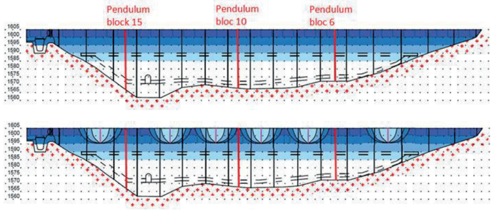
Crest length	300	m
Average strain	0.02%	
Elasticly recoverable strain	0.01%	
Expected strain recovery	30	mm
Slot length	10	m
Expected slot closure	8	mm
Minimum required slots	4	

Table 2. Intervention characteristics



7. 2D FE model of concrete plate with slot: (a) mesh; (b) equivalent thermal load; (c) horizontal strain

Intervention proposal



8. Qualitative arch stresses before and after intervention of 6 slots scheme.

Conclusion

Diamond wire slot cutting is a promising technique for the many dams facing internal swelling. Many improvements can still be made in the understanding of the swelling behavior. For better surveillance, an update of the current legislation on dam safety requirements should contain some limit values for expanding concrete.

Acknoledgements

Ing. M. Cuska of *Axpo dam safety department* and Ing. F. Amberg of *Lombardi* for providing the information about the case study.

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Potential for future hydropower plants (HPPs) in Switzerland

Daniel Ehrbar, Lukas Schmocker, Daniel Farinotti, Robert Boes – VAW ETH Zurich

Introduction

Climate change leads to glacier retreat in the Swiss Alps (Fig. 1). This has a twofold impact on hydropower in the periglacial environment:
(a) new potential locations for HPP reservoirs become ice-free
(b) additional meltwater from glaciers may be available for production

Fig. 1: Retreat of Trift Glacier from 30 June 2004 (left) to 3 July 2014 [© VAW]

The Swiss Energy Strategy 2050 anticipates 37'400 GWh annual electricity production from hydropower in 2035. In 2016, the annual production reached 36'264 GWh. Therefore, a further annual potential of about 1'136 GWh needs to be exploited. This project investigates hydropower potential in Switzerland arising from glacier retreat.

Methods

Glacier runoff projections from Huss & Hock (2015) were used. Three different representative concentration pathways (RCP) and ten global circulation models (GCM) were applied to 1'576 Swiss glaciers.

Site selection was based on expected glacier runoff volumes. Fig. 2 shows annual runoff volumes in 2035 for RCP 4.5, which range up to 283 hm³ in the Aletsch Glaciers catchment. Ice-free sites with high runoff volumes were investigated further.

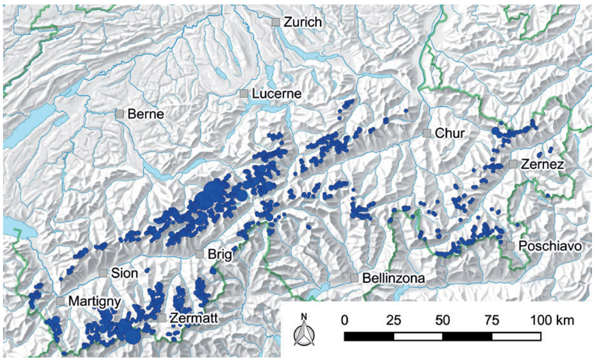

Fig. 2: Relative glacier runoff volumes in 2035 for RCP 4.5, with data from Farinotti *et al.* (2016) (largest dot represents 283 hm^3 annual discharge volume)

Site rating depended on a rating matrix where economy was weighted with 60%, environment with 25%, and society with 15%. Production, installed capacity, storage capacity, investment costs, and sediment continuity were the most important factors, each weighted with 10 or 11%. Reservoir sedimentation, vulnerability to natural hazards, impacts on land use and tourism, intrusion into protected areas, use for flood protection etc. were less important factors.

Results

Technical potential of eight future HPPs is given in Tab. 1. The calculations were conducted by Gauye *et al.* (2017) and Helfenberger *et al.* (2017), except for Trift Glacier. An annual technical potential of 1'171 GWh (from natural runoff, without pumped storage operation) is identified.

Tab. 1: Selected potential future hydropower plants

location [name of nearest glacier]	**annual production** [GWh]	**reservoir volume** [hm^3]
Aletsch Glaciers (all)	180	106
Baltschieder Glacier	74	27
Gorner Glacier	119	34
Grindelwald Glacier	130	92
Hüfi Glacier (Maderan valley)	171	60
Rhone Glacier	98	23
Roseg Glacier	253	89
Trift Glacier	146*	85*
total	**1'171**	**516**

* www.grimselstrom.ch/ausbauvorhaben/projekt-speichersee-und-kraftwerk-trift

Feasibility is given in general. Narrow gorges and steep rocky slopes provide favourable technical conditions (Fig. 3). The adoption of the Energy Strategy 2050 is an indication of social acceptance of hydropower, and it improves economical constraints. Nevertheless, building site preparation will be costly, and the integration into the existing dense hydropower network will be a major challenge.

Fig. 3: Visualisation of a potential hydropower reservoir at Gorner Glacier, from Farinotti *et al.* (2016)

Conclusions

The goals of the Energy Strategy 2050 concerning electricity supply from hydropower could be achieved with eight new large-scale storage reservoirs in the periglacial environment by 2035.

Acknowledgements

This project is financially supported by the Swiss National Science Foundation (SNSF) within the National Research Programme 70 "Energy Turnaround" Project No. 153927.

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Fine sediment management at hydropower schemes considering turbine erosion

D. Felix, I. Albayrak, R. Boes – VAW, ETH Zürich

Introduction

Rivers transport sediment particles of various sizes depending on the catchment properties, the season and the weather (Fig. 1). This is a challenge in the design and operation of hydropower plants (HPPs). Sediment deposits reduce the active storage of reservoirs (Fig. 2) and may compromise the operational safety of dams. High concentration of hard sediment particles in the turbine water cause turbine erosion mainly in medium- and high-head HPPs (Fig. 3). This has negative effects on the energy- and cost-efficiency, and eventually on the availability and safety of HPPs.
To mitigate these negative effects, strategies for the sediment management at reservoirs and HPPs are of prime importance.

Fig. 1: Mountain stream transporting sediment (Wysswasser downstream of the Fieschergletscher, Valais; picture: VAW 2013) with microscope image of suspended sediment particles (IGT, ETH Zürich; Felix 2017).

Fig. 2: Fine sediment deposits in a HPP reservoir (Reservoir Turtman, Valais; Schleiss 2005).

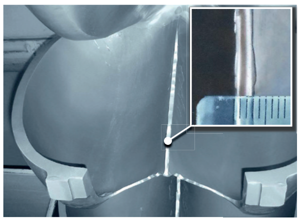

Fig. 3: Hydro-abrasive erosion on a Pelton turbine runner (HPP Fieschertal, Gommerkraftwerke AG; Felix 2017).

Reducing the sediment load in the turbine water of run-of-river HPPs by temporary shutdowns

During and after heavy precipitations (summer thunderstorms) the river discharge increases and the suspended sediment concentration (SSC) may rise by a factor of 100 compared to normal summer conditions. Moreover, coarser sediment particles are transported.
In such conditions, turbine erosion progresses faster than usual and the erosion-induced costs per kWh may exceed the electricity price.
If permitted by the regulatory framework and production obligations, it is therefore beneficial to close water intakes and to pause turbine operation in periods of high sediment load. Figure 4 shows an example of a shutdown scenario, which would have prevented consequential costs corresponding to almost 3% of the usual annual revenue.

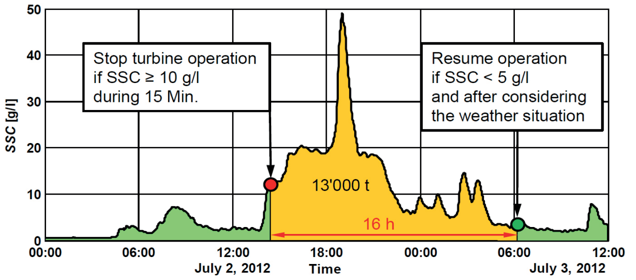

Fig. 4: Time series of suspended sediment concentration (SSC) in the power waterway of HPP Fieschertal during a major flood event with shutdown scenario. The orange area shows the sediment load which would have been prevented from passing the turbines (Felix 2017).

Increasing the fine sediment load in the turbine water of storage HPPs to reduce reservoir sedimentation

In reservoir lakes serving for seasonal storage, a large part of the incoming sediment particles settle. Hence, reservoir sedimentation is becoming a problem in the medium and long term.
There are various countermeasures to reduce the sediment input and to increase the sediment output from a reservoir. Occasional sediment release at the dam toe, as typically in flushing operations, causes temporarily high SSC which may have negative ecological effects. Another option to reduce reservoir sedimentation and avoiding such high downstream SSC, is to increase the fine sediment transport through the power waterway (Fig. 5). As a consequence, the sediment-induced costs due to erosion of hydraulic machinery increase. The target SSC in the turbine water results from an economic trade-off between these costs and the value of avoided or restored active storage.

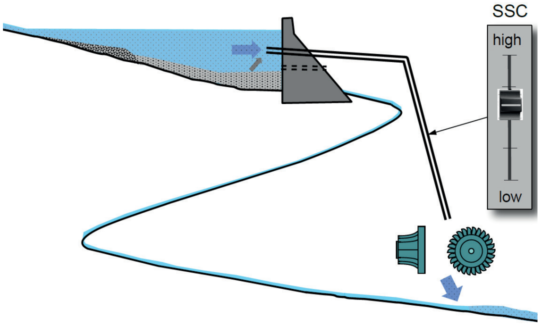

Fig. 5: Schematic of a storage HPP showing the option of increasing the suspended sediment concentration (SSC) in the turbine water to reduce reservoir sedimentation (Felix *et al.* 2017).

The SSC in the turbine water can be increased by reducing the sedimentation of particles inside the reservoir (e.g. by venting of turbidity currents or injection of water/air) or by hydraulic transport of fine sediment from the reservoir bottom in front of the power water intake (by hydro-suction or air-lift).

Conclusion and Outlook

Techniques to monitor the sediment situation (in real-time), turbine erosion and efficiency changes are available. Sediment and erosion data from field studies allow to calibrate and validate analytical models for turbine erosion prediction (e.g. IEC 62364 2013, Felix 2017).
In combination with economic analyses, such data and models serve as a basis to improve the operation of HPPs. Depending on the HPP layout, the natural conditions, and the time horizon for optimization, it is economically favourable to reduce or to increase the sediment concentration in the turbine water.

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Blocking probability at spillway inlets under driftwood impact

Paloma Furlan, M. Pfister, J. Matos and A.J. Schleiss*
**corresponding author: paloma.furlan@epfl.ch*

Introduction

Large Woody Debris (LWD) have a great influence in the ecosystem and geomorphology of a river, but it can also be considered dangerous when entering in contact with hydraulic constructions (Fig 1).

Figure 1: Picture from downstream of San Clemente Dam, USA. (NOAA)

Accumulation and blockage of floating material at spillway inlets can lead to significant problems as it might interfere with the normal functioning of the structure and avoid the safe pass of a flood. If it continues to accumulate, effects of floods, scouring or sediment deposition will be intensified. Knowledge of LWD blockage process is vital regarding safety evaluation of dams.

The present research project aims to describe and quantify systematically the influence of LWD characteristics on the blocking process and the effects a blockage can have on the rating curve of an ogee crested spillway with piers.

Methodology and experiments

A physical model was designed and constructed in the facilities of LCH (Fig 2). An ogee crested spillway with round nose piers was chosen as it is a widely used structure and has a great ability to pass floods.

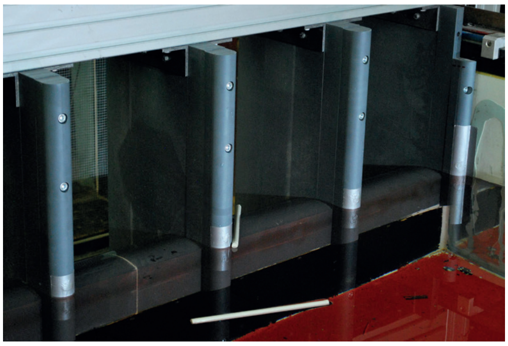

Figure 2: Picture from upstream of the experimental facility at LCH

Different configurations of experiments are being tested, always having a reservoir approach. In Fig 3, a single stem experiment can be seen.

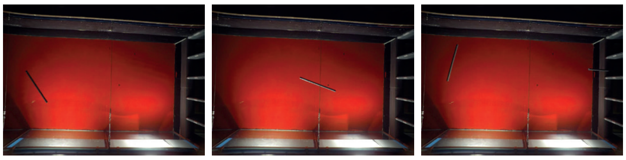

Figure 3: Picture from above the experimental facility at LCH

Parameters

The aim is estimating blocking probabilities in relation to:

- **Number of experimental repetitions**;
- **Density** of floating material;
- **Length and diameter** of LWD;
- **Group influence** and interactions between LWD;
- Amount of functioning **bays**;
- **Volume** of LWD blocked and **head increase**;

Preliminary results

“How many times should an experiment be repeated until it gives reliable results?” It is a commonly asked question among researchers involved with LWD studies. Different mathematical tools can give a good overview of the accuracy achieved from an experiment by means of confidence intervals.

This question was approached with individual stem experiments where different hydraulic conditions were established and systematically tested. The results were considered binomial as a stem could pass or block and the blocking probability was computed as follows:

$$\Pi(i) = \frac{\sum blocked\ stems}{\sum provided\ stems}$$

To understand the influence of density for blocking probabilities different stem densities were tested with constant initial conditions. Fig 4 shows the blocking probabilities obtained for one stem in function of its density (normalized with the density of water) after 30 repetitions of the experiment.

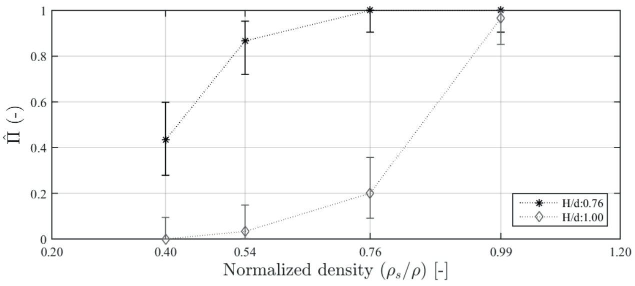

Figure 4: Blocking probability estimation in function of density

The different lines represent two different hydraulic conditions. It can be seen how an increment of density increases the blocking probability under the tested conditions for one size of stem.

Conclusions

Blocking probabilities of large woody debris is a random process, nevertheless with a statistical approach some open questions can be clarified. A wide spectrum of combinations has been tested to analyze the **replications** and its influence. For blockage experiments of individual stems, results can be considered statistically reliable at 30 repetitions (error in the estimation of blocking probability smaller than 0.09 with 90% confidence).

Systematic experiments to quantify the influence of **density** in blocking probabilities have been made and are being analysed. Different sizes of stems were tested with different transport regimes. In the next phase of work, analysis of **head increments** due to a blocked volume of large woody debris will be made.

Acknowledgments

This research project is developed in the scope of the Ph.D. Thesis by Paloma Furlan under the joint IST-EPFL doctoral program H2Doc. It is funded by the Portuguese Foundation for Science and Technology, LCH-EPFL and EDF.

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Exploitation optimale de la force hydraulique de la Plessur dans les Grisons (CH)

LCH
LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Introduction

La Plessur s'écoule dans la vallée du Schanfigg d'Arosa à Coire dans le canton des Grisons. Actuellement, trois aménagements en cascade utilisent la force hydraulique de cette rivière. Les paliers supérieur (KW Litzirüti) et inférieur (KW Chur - Sand) ont été récemment rénovés. Les installations du niveau intermédiaire (KW Lüen) ont déjà plus de 100 ans et méritent une réhabilitation. De plus, une chute de 400 m entre les aménagement supérieur et inférieur reste inexploitée. Le but de ce projet est donc de proposer une variante permettant d'utiliser idéalement ce tronçon médian en tenant compte des contraintes extérieures et des aménagements existants.

Méthodologie

Après une étude du contexte, de l'environnement et des installations existantes, une analyse multicritère a été menée dans le but de définir le tracé optimal. Les aspects techniques, fonctionnels, économiques et environnementaux ont été pris en compte pour cet examen. Un pré-dimensionnement de neuf variantes a été réalisé sur la base d'hypothèses simplificatrices. Le passage en rive droite ou en rive gauche, l'utilisation d'affluents latéraux ou encore l'intégration de l'aménagement intermédiaire définissent les différents tracés.
La variante retenue a ensuite été dimensionnée jusqu'au stade d'avant projet.

Variante retenue

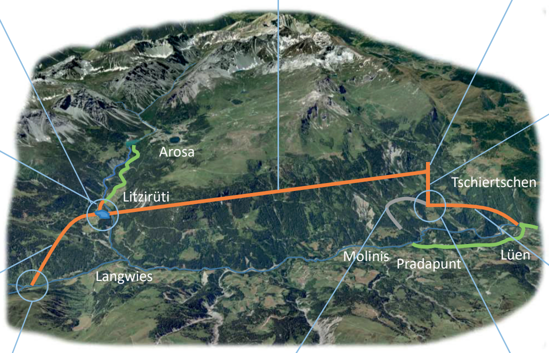
Galerie d'amenée principale		
Longueur	6752	m
Pente	4.00	‰
Diamètre d'excavation	3.40	m
Diamètre intérieur	≈ 2.85	m

Site de Litzirüti - Plessur		
Rejet maximal de la centrale	3.0	m³/s
Débit de la prise d'eau	5.0	m³/s
Niveau de la prise d'eau	1390.0	msm
Capacité du dessableur Bieri	5.0	m³/s

Bassin de compensation		
Volume total	67'000	m³
Niveau maximal	1388.0	msm
Niveau minimal	1374.0	msm
Niveau de la prise d'eau	1371.8	msm

Galerie d'amenée		
Longueur	2452	m
Pente	3.00	‰
Diamètre d'excavation	3.40	m
Diamètre intérieur	≈ 2.85	m

Site sur le Sapünerbach et Fondeierbach		
Débit de la prise d'eau	3.5	m³/s
Niveau de la prise d'eau	1400.0	msm
Capacité du dessableur Bieri	3.5	m³/s



Galerie d'accès à la centrale		
Longueur	3489	m
Pente	10.0	%
Diamètre d'excavation	6.20	m

Cheminée d'équilibre		
Niveau supérieur	1493.3	m
Niveau inférieur	1346.3	m
Oscillation maximale	1443.9	m
Oscillation minimale	1355.7	m
Diamètre de la cheminée	1.6	m
Diamètre de l'épanouissement	5.0	m
Hauteur de l'épanouissement	20.0	m

Puits vertical		
Hauteur du puits	554.6	m
Diamètre intérieur	1.6	m
Épaisseur du revêtement béton	40	cm
Diamètre de l'armature	16	mm
Espacement de l'armature	15	cm

Galerie de fuite		
Longueur	2540	m
Pente	3.00	‰
Diamètre d'excavation	3.40	m
Diamètre intérieur	≈ 2.85	m

Centrale souterraine		
Débit équipé	2 x 4.25	m³/s
Puissance installée	44.57	MW
Axe des turbines	785.0	msm
Diamètre des turbines Pelton	2.21	m
Nombre d'augets	26	-
Épaisseur du blindage	54	mm

Fig. 1: Présentation de la variante retenue

Production et aspects économiques

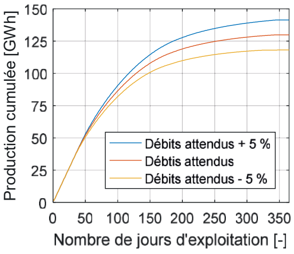


Fig. 2: Production annuelle attendue

Aspects économiques		
Coûts de construction	244.0	Mio CHF
Durée des travaux	env. 2	ans
Volume des excavations	330'000	m³
Chute brute maximale	603.0	m
Chute nette maximale	592.1	m
Production annuelle	129.9	GWh/an
Pertes pour KW Lüen	20.5	GWh/an
Prix de revient par kWh	15.92	Ct./kWh
Investissement par KW	5475	CHF/kW

Tab. 1: Aspects économiques de la variante retenue

Conclusion

La variante retenue demande la mise en place de moyens de construction lourds. De plus, l'investissement initial est conséquent. Ceci induit un risque financier accru pour la réalisation du projet. Le prix de revient est lui aussi relativement élevé.

Malgré ces incertitudes économiques, la variante retenue exploite de manière optimale le grand potentiel de la vallée du Schanfigg et permet d'accroître de manière significative la production hydroélectrique locale et indigène. Le bénéfice escompté tend donc à dominer le risque financier.

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Air demand of bottom outlets

Benjamin Hohermuth, Lukas Schmocker, Robert Boes – VAW, ETHZ

Motivation and Objectives

Bottom outlets are a key safety feature of large dams. Future demands on bottom outlets will likely increase due to (i) dam heightening as promoted by the Swiss energy strategy 2050 and (ii) more frequent sediment flushing due to increasing reservoir sedimentation rates. Bottom outlets frequently encounter problems with cavitation damage, gate vibration and flow chocking. These problems can be mitigated by sufficient aeration. However, current knowledge does not allow for a coherent design of the air vent. This project aims to improve air demand design equations by including the effects of

- Energy Head H_E
- Relative gate opening a/a_{max}
- Air vent loss coefficient ζ
- Tunnel length L
- Tunnel slope S_o

Hydraulic model tests

The hydraulic Froude scale model has an approximate scale of 1:5 to 1:10, thereby representing a typical bottom outlet in Switzerland. It features a rectangular tunnel cross-section with a maximum length of 20.7 m (Fig. 1). Two high-head pumps deliver a discharge Q_w up to 600 l/s at an energy head H_E of 30 m w.c. at the gate. The investigated parameter range is shown in Figure 2.

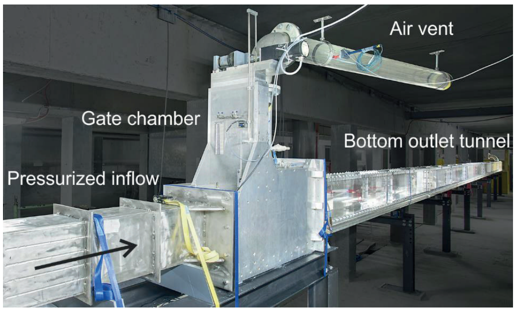

Fig. 1: Hydraulic scale model at Laboratory of Hydraulics, Hydrology and Glaciology (VAW)

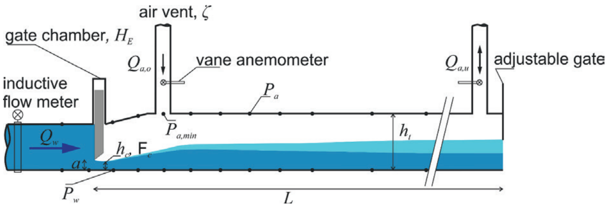

Fig. 2: Model setup and notation

Tunnel width	$W = 0.2$ m	Relative gate opening	$a/a_{max} = 0.1 - 0.8$
Tunnel height	$h_t = 0.3$ m	Water discharge	$Q_w = 60 - 600$ l/s
Tunnel length	$L = 20.6, 12.6, 6.6$ m	Air vent loss coefficient	$\zeta = 0.7 - 37$
Energy head	$H_E = 5 - 30$ m w.c.	Tunnel slope	$S_o = 0 - 0.03$

Results

Air discharge through the air vent $Q_{a,o}$ increases with increasing H_E (Fig. 3a, c). An increase in $Q_{a,o}$ is observed for small a/a_{max} due to the formation of spray flow (Fig. 3a). $Q_{a,o}$ increases with increasing a/a_{max} for free surface flow conditions at moderate gate openings. For large a/a_{max} and high H_E, $Q_{a,o}$ drops considerably due to the formation of foamy flow (full flowing tunnel, Fig. 3a).

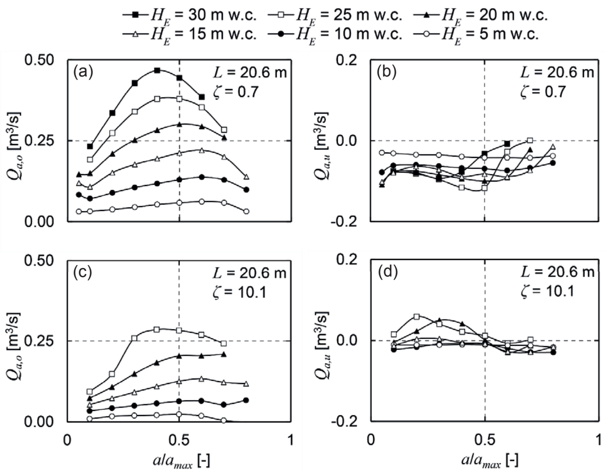

Fig. 3: Air discharge through air vent (a), (c) and from tunnel end (b), (d) as a function of relative gate opening for different energy heads and air vent loss coefficients.

The air discharge from the tunnel end $Q_{a,u}$ is always negative, indicating that air is flowing out of the tunnel for the given tunnel configuration (Fig. 3b). An increase in ζ leads on the one hand to an overall decrease in $Q_{a,o}$ (Fig. 3c). On the other hand $Q_{a,u}$ increases and the positive values indicate air flowing into the tunnel, leading to a counter-current air flow (Fig. 3d). A similar effect is observed if the tunnel length is reduced. Strong counter-current air flows, especially in long tunnels, can lead to intermittent flow chocking.

Discussion and Outlook

Air demand is usually defined as the ratio between the air and the water discharge $\beta = Q_a/Q_w$. For a given tunnel and air vent geometry, β is mainly a function of the Froude number at the vena contracta F_c (Fig. 4). However, the fits are shifted downwards with increasing ζ (Fig. 4a) and decreasing L, respectively (Fig. 4b).

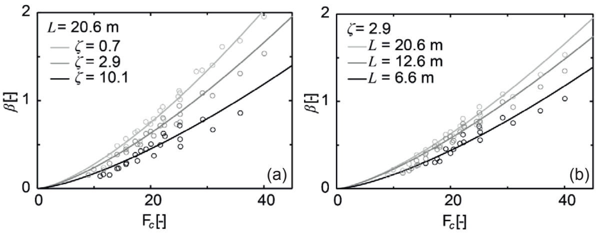

Fig. 4: Air demand β as a function of F_c for (a) increasing air vent loss ζ and (b) decreasing tunnel length L.

These preliminary results show that hydraulic model tests can be used to investigate the effect of different – previously not considered – parameters on the air demand. Thus, the design and the operational safety of bottom outlets can be improved with systematic experimental modelling techniques.

Acknowledgement

This project is financed by the Swiss National Science Foundation (Grant Nr. 163415) and is embedded in the Swiss Competence Centre for Energy Research - Supply of Energy (SCCER-SoE) framework.

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Hydropower potential at *Rhône Glacier*

Valeria Hutter, Daniel Ehrbar, Lukas Schmocker, Daniel Farinotti, Robert Boes – VAW ETH Zurich

Introduction

Climate change causes glacier retreat, and recently glaciated locations become ice-free. These sites may be used for hydropower production. The Swiss Energy Strategy 2050 supports additional production within the periglacial environment. *Rhône Glacier* is a potential site for a future hydropower plant, as a new lake – *Rottensee* – starts forming.

Boundary conditions

On 21 May 2017, the first package of measures of Energy Strategy 2050 was accepted by popular vote. Large-scale hydropower shall become more competitive again by means of investment subsidies, market premium or status of national interest.

Important boundary conditions that need to be taken into account within the project perimeter are:
- pasture landscape,
- BLN object 1710 "*Rhône Glacier* with forefield",
- the already existing hydropower network,
- tourism at *Rhône Glacier*, and
- the future runoff evolution due to climate change

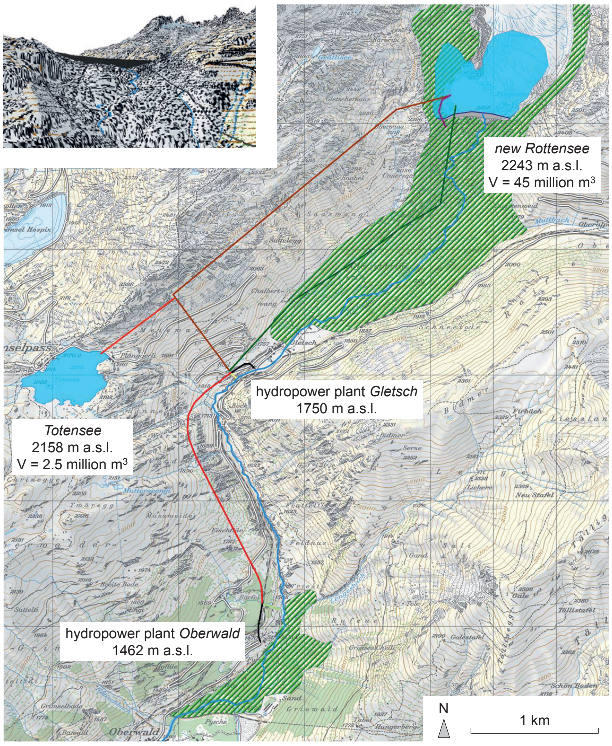

Fig. 1: Topographical map of the project perimeter with the different parts of the project and the most relevant boundary conditions (in red: power waterways, in green: floodplain / meadow) [© swisstopo]
inset: Visualisation of the dam as seen from *Furka* pass [© swisstopo]

Concepts

Different concepts were developed and compared to each other by applying a rating matrix, accounting for economy, environment, and society. The selected concept is sketched in Fig. 1, integrating the new *Rottensee* into the existing hydropower network.

Layouts and dimensions

4 different layouts were investigated for the best concept. Governing factors are:
- design discharge and number of turbines,
- ratio of reservoir volume to annual inflow,
- hydraulic head, and
- location of waterways (surface or underground).

Reservoir

The reservoir will have a volume of circa 45 million m^3 in 2065; the dam height will be 38 m (Schleiss 2017). Due to earthquake risks and topographical constraints, a gravity dam is recommended.

Discharge

A semi-baseload power station with more than 4'000 production hours per year will result in a design discharge of circa 3.1 m^3/s at *Rottensee* and 0.25 m^3/s at *Totensee*.

Head

Maximum head is 493 m at *Rottensee* and 408 m at *Totensee*.

Cost estimate

Costs vary between circa 150 and 160 million CHF, depending on the chosen layout (Fig. 2).

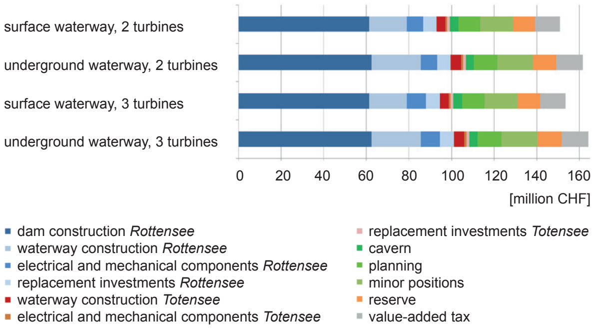

Fig. 2: Cost estimates for four layouts, based on Steiner & Vetsch (2010), Alvarado-Ancieta (2012), and VAW (2015)

Conclusions

A new reservoir for hydropower production could be built at *Rhône Glacier*. It would result in a production of ca. 55 GWh/a. Production costs would be 0.12–0.18 CHF/kWh, depending on the layout.

Acknowledgements

This project is financially supported by the Swiss National Science Foundation (SNSF) within the National Research Programme 70 "Energy Turnaround" Project No. 153927. The collaboration of Forces Motrices Valaisannes (FMV) is gratefully acknowledged.

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Online prediction tool for hydropower energy (Opt-HE)

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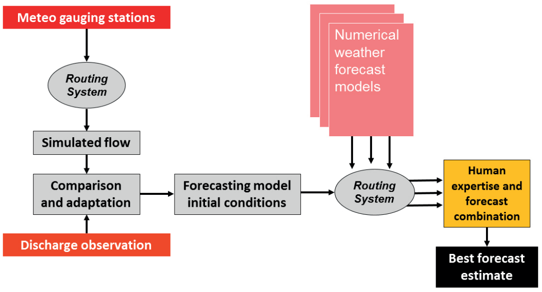
The OPT-HE project

OPT-HE : Optimal Prediction Tool for HydroElectricity

Hydrological prediction is a key factor in the optimization of hydropower production, by limiting the water spillings and increasing the water value. These objectives are perfectly in line with the *Energy Strategy 2050,* allowing an increase of the total electricity production with no new impact on the environment.
The partners of the project are five hydropower suppliers, MeteoSwiss and Hydrique Engineers.
The research is realized by Hydrique Engineers, the Laboratory of Hydraulic Constructions (EPFL) and the Institute for Climate and Atmosphere (ETHZ).

Structure of the project

The existing forecasting system at Hydrique Engineers is based on rainfall-runoff simulation, combining the assimilation of discharge gauging stations and human expertise. All these single processes are to be optimized within this project. Four workpackages are completed: general methodology, weather forecast, hydrological processes, operation.



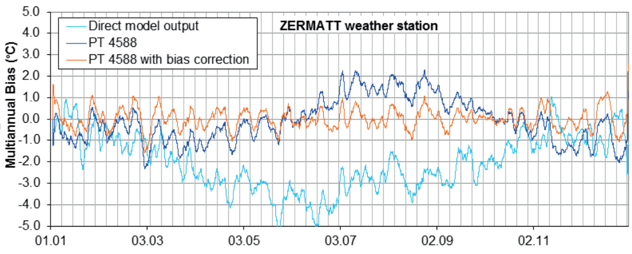
Outcomes

For this project, various tests have been realized, focusing on the specific characteristics of the catchment areas. As the existing system already had a satisfying performance, it was difficult to highlight improvements in the different methods showing a high performance. Out of the 18 different methods tested within the simulation and operation processes, 5 methods have been directly implemented. 3 additional methods, with less impact, have also been applied in the operational forecasting system at Hydrique.

Type of catchment area	Glacier	Prealpine	Jura-region	Added value
Temperature forecast bias	In operation			Very good
Analysis of the sources of forecast error		In operation	In operation	Very good
Influence of new precipitation stations			Rejected	Poor
Glacier model postprocessing with spline correction	In operation			Very good
Discharge assimilation in automatic correction	In operation	In operation	In operation	Very good
Uncertainty quantification and forecast	In operation	In operation	In operation	Very good
Combined glacier model with simulation and machine learning	In operation			Good
Assimilation of CombiPrecip data		Rejected	Rejected	Poor
Precipitation forecast quality assessement		In operation	In operation	Good
Pre-processing of stochastic weather forecast (COSMO-E)	In operation	In operation	In operation	Good
Seasonal forecasting	Rejected	In operation		Good
Precipitation forecast bias		Rejected	Rejected	Poor
Assimilation of COSMO-1 high-resolution forecast		In operation	In operation	Good
Use of COSMO-E instead of sensitivity method for the uncertainty prediction	Rejected	Rejected	Rejected	Poor
Short-term precipitation forecast by combination of observation and numerical weather forecast	Rejected	Rejected	Rejected	Poor
Post-processing of runoff forecasts using previous runs	Rejected	Rejected		Poor
Validation tests of the combined new methods	In operation	In operation	In operation	Very good
Inflow forecast by neural networks	Rejected	Rejected	Rejected	Poor
Influence of vegetation cover interception	Rejected	Rejected	Rejected	Poor

Correction of temperature biases

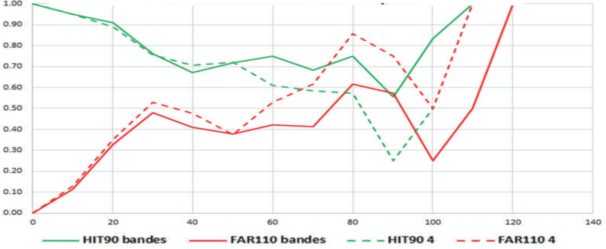
One of the major source of uncertainty in the inflow prediction for glacier catchments is due to the air temperature forecast. The direct model outputs (light blue) cannot be used. The choice of selected model outputs at locations different from the station, including a systematic bias correction, provide better results (blue and orange lines).
The figure below shows the multiannual bias for the Zermatt station for the COSMO7 model, over 7 years of analysis.



Assimilation of COSMO1 precipitation forecast

The increasing resolution of meteorological models requires an improved integration of the direct model output into the rainfall-runoff model. Indeed, the new assimilation method (*bandes*) attributes model grid points according to the real geometry of the catchment area. In some cases, it provides slightly better outcomes.
The figure below shows the improvements obtained by this method. Both the HIT (proportion above a threshold) and FAR (proportion below a threshold) indicators could be improved at the Montsalvens catchment area in the Sarine river.

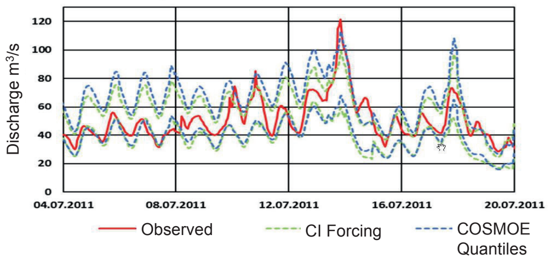
HIT and FAR indicators for COSMO2 forecasts at Monsalvens (Sarine river)



New method for the uncertainty range forecast

Three different models were tested to produce an uncertainty range for the prediction (CI), like statistical confidence interval, quantiles out of probabilistic weather models (COSMOE quantiles) and preliminary meteorological forcing (± 2°C and ± 20% precipitation). The preliminary meteorological forcing of precipitation and temperature results in thinner uncertainty range than the two other methods, for a similar success rate.

Uncertainty range at the Massa river catchment



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Utilisation optimale du potentiel hydroélectrique d'un bassin versant alpin: le barrage de Khudoni en Géorgie

Jordan M. (1)(2), *Venuleo S.*(1), *Manso P. A.*(1), *Schleiss A. J.*(1)

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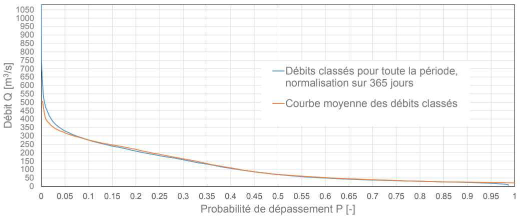
LCH LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Objectifs

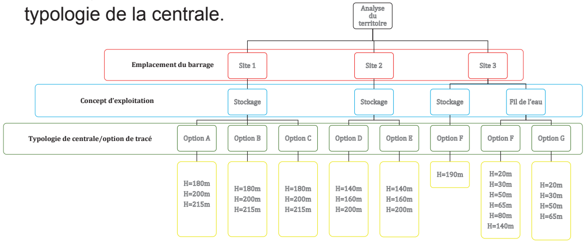
Contexte local	
Pays	Géorgie
Province	Svanétie
Apports moyens annuels (réf. Site 1)	3847 hm³
Bassin versant	Enguri (2780 km²)
Production de sédiments	97 kg/sec. En 1976
Magnitude (Richter)	M=9
Début du projet/Arrêt	1979/1989
Avancement de la réalisation en 1989	25% des travaux
Restauration du projet	2005



- ➢ Les constructions existantes (25%) ont biaisé le choix du site du barrage.
- ➢ Les impacts socio-environnementaux liés à l'inondation de Khaishi sont inacceptables.

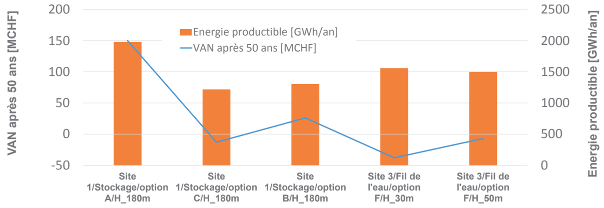
Etude de variantes

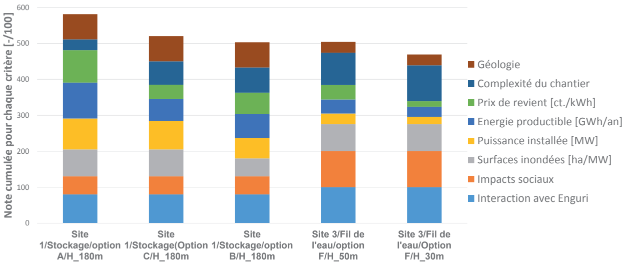
- Pour l'étude de variantes, **trois sites** différents de barrage, avec des concepts d'exploitation de stockage et au fil de l'eau sont évalués, en faisant varier à la fois la hauteur de la retenue et la typologie de la centrale.


Analyse du territoire
Emplacement du barrage
Site 1
Site 2
Site 3
Concept d'exploitation
Stockage
Stockage
Stockage
Fil de l'eau
Typologie de centrale/option de tracé
Option A
Option B
Option C
Option D
Option E
Option F
Option F
Option G
H=180m H=200m H=215m
H=180m H=200m H=215m
H=180m H=200m H=215m
H=140m H=160m H=200m
H=140m H=160m H=200m
H=190m
H=20m H=30m H=50m H=65m H=80m H=140m
H=20m H=30m H=50m H=65m

Analyse multicritères

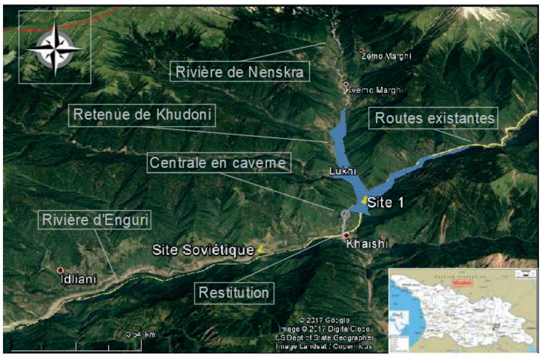
- Après un tri préliminaire, les variantes sont évaluées à partir de critères quantitatifs avant d'utiliser une même échelle de notation de 0 à 100 points pour chaque critère.
- Le **site 1** en amont de Khaishi et en aval de la confluence avec la rivière de Nenskra est retenu et représente une alternative au concept soviétique initial.



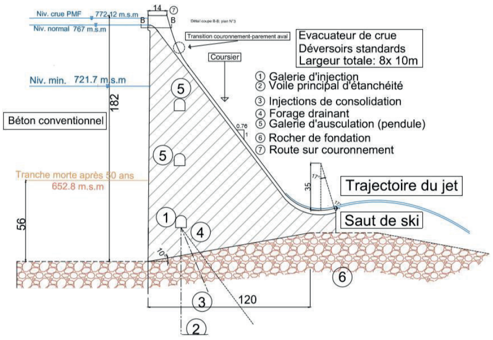


Concept et variante retenue

- Une variante avec **concept d'exploitation de stockage** avec une **gestion intra-annuelle au fil de l'eau en été** est choisie.
- L'énergie de pointe est fournie en été, avec des exportations vers la Turquie, l'Arménie, la Russie, et l'Azerbaïdjan.



Variante retenue	
Hauteur du barrage	182m
Volume utile de la retenue	96 hm³
Hauteur tranche morte/durée de vie utile	56m/93 ans
Puissance installée	551 MW (3 groupes Francis de 184 MW)
Débit équipé	310 m³/s
Energie productible annuelle	2008 GWh/an
Coût total/Coût du barrage	1.08 GCHF/434 MCHF
Gains annuels	100 MCHF
Prix de revient après 50 ans (i=8%)	4.1 ct./kWh
Zones inondées	445 ha/MW
Déplacement de population	Village de Lukhi/Env. 40 personnes
Durée des travaux	7 ans
Nouvelles infrastructures d'accès	2 ponts/1 tunnel/env. 10km de nouvelles routes



Evacuateur de crue
Déversoirs standards
Largeur totale: 8x 10m

① Galerie d'injection
② Voile principal d'étanchéité
③ Injections de consolidation
④ Forage drainant
⑤ Galerie d'ausculation (pendule)
⑥ Rocher de fondation
⑦ Route sur couronnement

Trajectoire du jet

Saut de ski

Discussion

- La retenue peut être remplie **40 fois durant une année.**
- Le nouveau concept de Khudoni permet une puissance installée de 551 MW.
- Une puissance moyenne annuelle de 228 MW pour un **marnage faible de 40m.** Puissance moyenne en février: 46 MW
- La variante grand barrage pour maximiser la chute et la puissance installée.
- Cascade de la rivière d'Enguri avec les aménagements d'Enguri (1300 MW) et de Vardnili (340 MW) à l'aval de Khudoni.
- Projet compatible avec une extension future sur le site 3, à l'aval
- **Stratégie 1**: Maximiser la puissance installée
- **Stratégie 2**: Maximiser l'énergie annuelle productible
- **Stratégie 3**: Minimiser les investissements
- Un plan opérationnel de gestion de sédiments avec un tunnel de by-pass est nécessaire.

Remerciements

Un grand merci au bureau ***Stucky SA*** de Renens pour les données de base hydrologiques qui ont permis la réalisation de cette étude et en particulier au chef de projet Juliano Ribeiro pour son aide.

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Operation changes of a complex hydropower system over decades

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Motivation

Both the production and consumption of electricity are undergoing profound changes. If the disruption caused by new technologies and the political shift towards renewable sources, as well as societal awareness of climate change, have modified the energy market and will likely to continue to do so, the changing climate has the potential to affect hydrology, both directly the precipitation [1] and, even more so, snow and ice melt. It is important to understand the past to understand how complex hydropower systems may adapt to a quickly changing world.

Case study

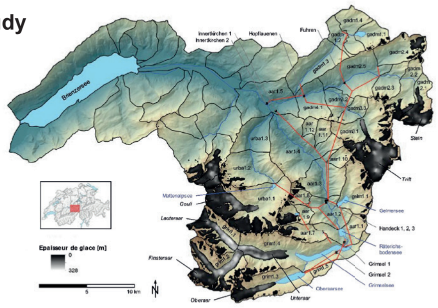

Fig 1. The KWO system and estimated glacier cover in 1993 [2].

Here, the Kraftwerke Oberhasli AG (KWO) hydropower system (Fig. 1) is viewed from production and market perspectives.

- 10 power plants,
- 29 turbines,
- 1368 MW.
- 4 main reservoirs.

Energy market

Since its inception, the SPOT energy price has decreased. evidences clear seasonal (Fig. 2), weekly, and daily trends that can be exploited by hydropower schemes with storage and pump-storage capabilities.

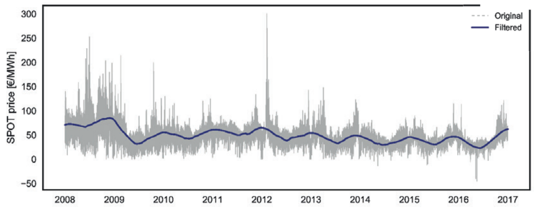

Fig 2. SPOT energy prices in Switzerland (day-ahead, www.epexspot.com).

Hydrology

The overall water available to the system did not undergo dramatic changes over the last decades (Fig. 3).

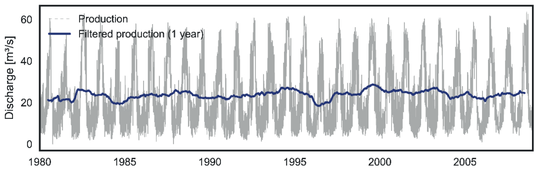

Fig 3. Historical KWO outflows (Innertkirchen 1 plus 2).

Acknowledgements

We are thankful for the support provided by KWO and the Swiss Commission for Technology and Innovation (CTI), which provided the bulk of the funding through project 17902.3 PFIW-IW.

But part of the inflows are due to glacier melting (Fig.4), which will eventually run out as the snow and ice cover reaches an equilibrium [3] .

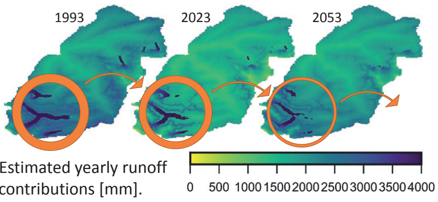

Fig 4. Estimated yearly runoff contributions [mm].

The system: results and conclusions.

Looking at the fluxes of the system (Sankey plot, Fig. 5) and clustering techniques (K-means, Fig. 6), one can isolate the main modes of operation. Insight is gained into daily, seasonal, and long term operations (Fig. 7). According from Fig. 7, pump-storage operations (e.g. Oberaar-Grimsel) have changed more significantly than the lower part of the cascade.

Since 1980, the system has responded much more to energy demand and market than to hydrology. Increasingly, the system adapts to seize intra-weekly and intra-daily opportunities.

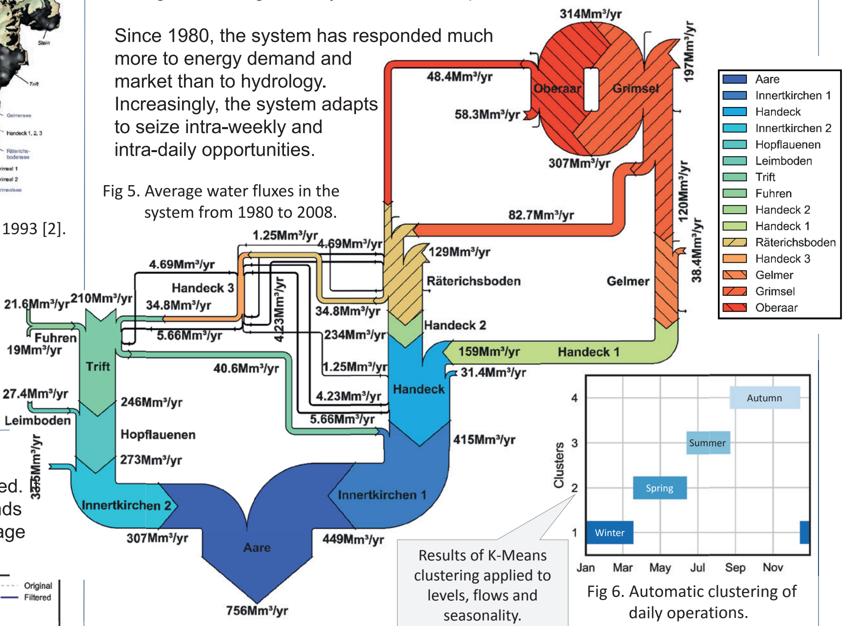

Fig 5. Average water fluxes in the system from 1980 to 2008.

Results of K-Means clustering applied to levels, flows and seasonality.

Fig 6. Automatic clustering of daily operations.

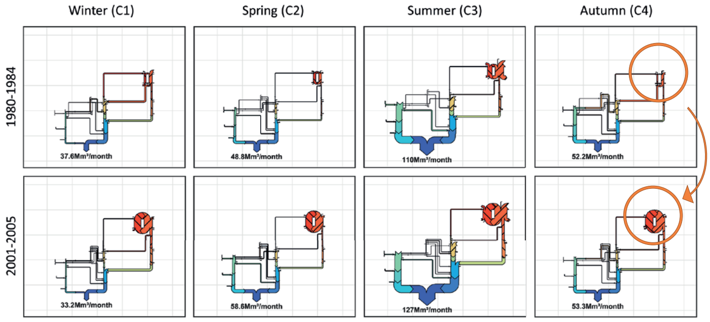

Fig 7. Evolution of the system through time; early 1980's vs early 2000's.

References

[1] G. Blöschl et al., Changing climate shifts timing of European floods. Science, 357 (6351), 2017.
[2] M. P. Bieri, Operation of Complex Hydropower Schemes and its Impact on the Flow Regime in the Downstream River System under Changing Scenarios. Thèse EPFL, n° 5433, 2012.
[3] S. Terrier et al., Impact du retrait glaciaire et adaptation du potentiel hydroélectrique dans les Alpes suisses, La Houille Blanche, 2015 (1).
[4] Matos et al., The operation of a complex Alpine hydropower scheme across four decades (working title), in preparation.

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Evaluation du potentiel d'augmentation du stockage saisonnier d'énergie en Suisse en vue des changements climatiques

Monay Blaise, Dr. Manso Pedro, Dujardin Jérôme, Dr. Massimiliano Zappa, Prof. Schleiss Anton
Laboratoire de Constructions Hydrauliques, EPFL, Station 18, CH-1015 Lausanne

Approche

L'énergie d'origine hydraulique en Suisse représente plus de 60% de la production totale d'énergie pour un réseau hydrographique quasiment exploité à son maximum. La capacité des lacs d'accumulation ne représente que 42% de leur production totale annuelle, ce qui conduit les centrales à accumulation, à la fin du semestre d'été, à devoir turbiner les apports au fil de l'eau. Une partie de la production d'énergie ne peut, par conséquent, pas être concentrée sur le semestre d'hiver, ce qui conduit la Suisse à devoir importer massivement de l'électricité. La capacité de stockage d'énergie doit par conséquent être augmentée, elle permettra également de soutenir le développement des énergie renouvelables et l'abandon du nucléaire dans le cadre de la Stratégie Energétique 2050.

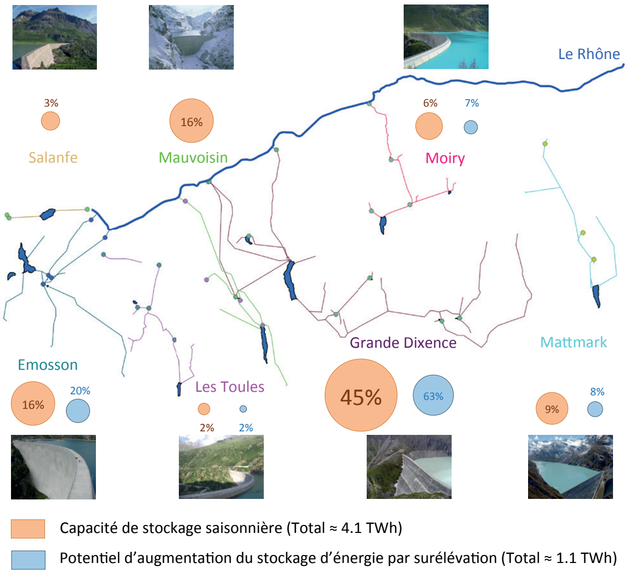
Evaluation du potentiel d'augmentation du stockage saisonnier

La capacité de stockage saisonnière d'un aménagement est définie comme suit:

$$CSS = CE * V_{Utile}$$

CSS : Capacité de stockage saisonnière [GWh]
CE : Coefficient énergétique [kWh/m^3]
V_{Utile} : Volume utile [hm^3]

L'évaluation du potentiel d'augmentation de la capacité de stockage saisonnière (CSS') est effectuée par la mesure des surfaces entre les courbes de niveaux des bassins versants des retenues.

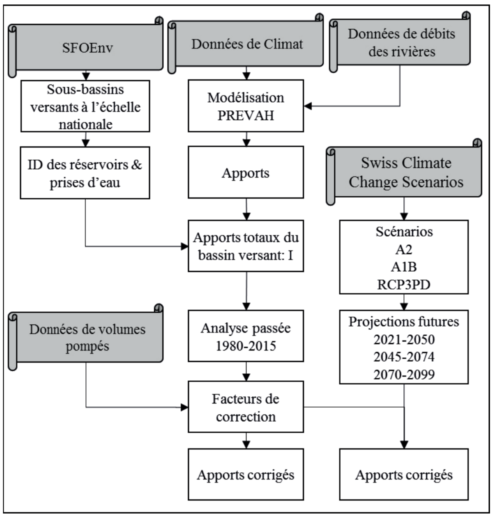


Le modèle hydrologique PREVAH et scénarios d'écoulements futurs

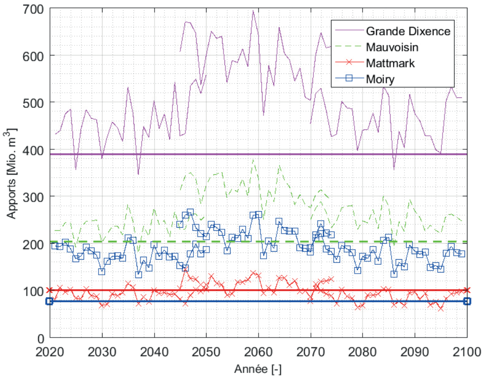
Le modèle hydrologique PREVAH permet d'évaluer les apports en eaux des retenues. Des coefficients de correction mensuels aux prises d'eau sont appliqués en comparant les données de PREVAH aux données de pompage afin de corriger les imprécisions du modèle, principalement dues aux débits résiduels des rivières, à la capacité limitée des prises d'eau et aux périodes de crues.

$$Apports\ totaux = \int_a^A \sum_{i=1}^{12} \left[\sum_{j=1}^{n} Q_{i,j} \cdot S_j + \sum_{j=1}^{p} \psi_{i,j} \sum_{k=1}^{t} Q_{i,j,k} \cdot S_k \right]$$

a & A: Première et dernière année de la période
n,p & t: Nombre de sous-bassins versants naturels, prises d'eau, sous-bassins versants de la prise d'eau
Q: Débit de ruissellement du sous-bassin versant natuel [hm^3/km^2]
S: Surface du sous-bassin versant [km^2]
ψ : Coefficient de captage de la prise d'eau, $\psi \epsilon [0; 1]$


SFOEnv
Données de Climat
Données de débits des rivières
Sous-bassins versants à l'échelle nationale
Modélisation PREVAH
ID des réservoirs & prises d'eau
Apports
Swiss Climate Change Scenarios
Apports totaux du bassin versant: I
Scénarios A2 A1B RCP3PD
Données de volumes pompés
Analyse passée 1980-2015
Projections futures 2021-2050 2045-2074 2070-2099
Facteurs de correction
Apports corrigés
Apports corrigés

Les volumes d'apports annuels des aménagements de Grande Dixence, Mauvoisin, Mattmark et Moiry à l'horizon 2100 sont présentés ci-dessous (les lignes horizontales représentent le volume utile des aménagements) :



Conclusions et perspectives

- La rive gauche du Rhône présente une capacité de stockage saisonnière de **4.2 TWh**, avec un potentiel d'augmentation de plus de **1 TWh** d'énergie.
- Davantage de volume utile est nécessaire afin de minimiser le turbinage au fil de l'eau des centrales à accumulation, en particulier pour la **période 2045-2074**.
- La retenue du **lac des Dix** est la plus favorable au stockage saisonnier, son coefficient énergétique est le plus élevé de la rive gauche du Rhône.
- L'**aménagement de la Grande Dixence** présente la plus importante augmentation de stockage saisonnier. Pour exploiter pleinement ce potentiel, des projets de pompage s'avèrent nécessaires.

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Confortement d'un barrage poids en maçonnerie présentant une légère courbure en plan : Le barrage de Cenne-Monestiés

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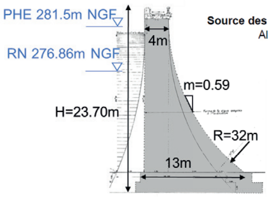
Objectifs

En raison d'une revue à la hausse de l'hydrologie et malgré un confortement ultérieur à l'aide de tirants précontraints appliqué en 1966, le barrage de Cenne-Monestiés (France) ne respecte plus les critères de stabilité et de sécurité actuels et nécessite un confortement.

Contexte



Coupe type

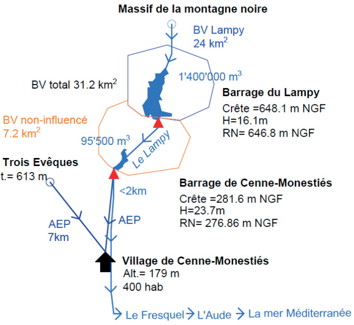
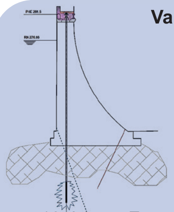


Schéma du système

Caractéristiques	
Type	Barrage poids en maçonnerie, courbure en plan
Date de construction	1883
Rivière	Le Lampy
Usage	Alimentation en eau potable (AEP)
Hauteur sur fondation	23,7m
Longueur en crête	95m
Rayon de courbure en plan	250m
Surface du bassin versant	31.2km²
Capacité utile du réservoir	95 500m³
Organes hydrauliques	Déversoir à seuil libre, 4 pertuis de vidange, 1 prise d'eau

Etude des variantes de confortement

Variante 1: Tirants post-contraints

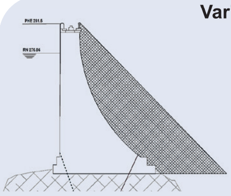


- L'accès au site est difficile et les tirants nécessitent une mise en œuvre légère.
- Les tirants existants limitent les possibilités de disposition.
- Ils exigent un entretien et suivi particuliers et sont sensibles aux infiltrations.

19 tirants $F_{tirants}$=3,6 - 6MN

Co*= 0,8 MCHF

Variante 2: Epaulement aval

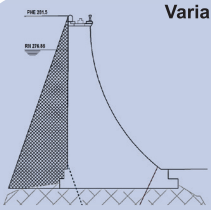


- La solution en béton apporte plus de sécurité en cas de surverses que des matériaux meubles.
- L'épaulement permet l'intégration de galeries et réadaptation des organes hydrauliques.
- Le volume de matériaux à mobiliser est important.

Vol. béton= 7900m³

Co= 2 MCHF

Variante 3: Inclinaison amont



- L'étanchéité du mur amont est réhabilitée.
- Offre la possibilité d'intégrer une galerie au pied amont pour mieux contrôler la fondation.
- Les travaux à l'amont perturberont l'AEP du barrage qui est l'unique captage (la source étant polluée).

Vol. béton= 4000m³

Co= 1,2 MCHF

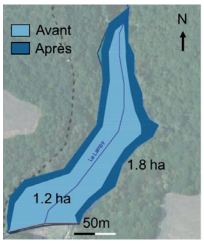
**Co = coûts de construction brut*

Avant-projet

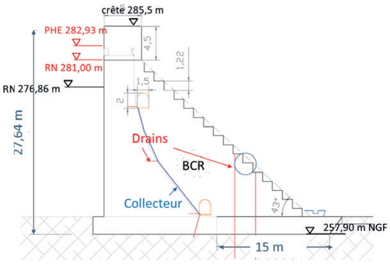
La variante 2 est améliorée avec une surélévation de l'ouvrage de 4m permettant le passage des crues en crête sur un déversoir en marches d'escalier.

	Avant	Après
Hauteur sur fondation	23,7m	27,6m
Niveau de la retenue normale	276.86m NGF	281.0m NGF
Niveau de crue de projet	281.50m NGF	282.93m NGF
Capacité utile du réservoir	95 500m³	187 200m³
Evacuateur de crues (non-vanné)	Rive gauche, 2 arches de 4m	Zone centrale, 3 passes de 11m
Vidanges de fond	4 pertuis contrôlés par 1 vanne	2 pertuis contrôlés par 2 vannes
Système de drainage	Aucun	Interface et épaulement

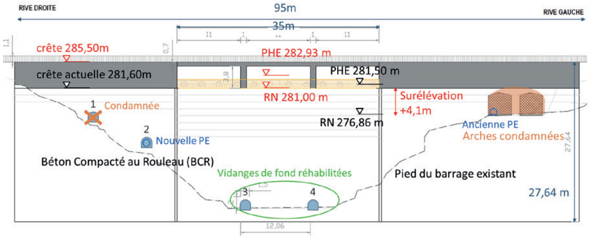
Economie	
Coût de construction confortement	2 MCHF
Coût de construction de la surélévation	1.3 MCHF
Prix de vente de l'eau (85 000m³/an)	1.06 CHF/m³



Vue en plan de la retenue



Coupe du barrage surélevé



Elévation aval

Conclusions

- La problématique de l'AEP est déterminante, le confortement à l'aval assure la stabilité du barrage sans perturber l'exploitation.
- À court terme la variante 1 (tirants) implique les coûts les plus faibles mais elle doit être intégrer la remise en état de l'évacuateur de crues. La variante retenue est une réponse à long terme qui valorise le réservoir avec un nouveau modèle économique.
- La méthodologie de réalisation de l'épaulement doit faire l'objet d'études de stabilité détaillée. La géométrie (fruit, crête etc.) doit être optimisée.

Références

CFBR, Recommandations pour la justification de la stabilité des barrages-poids, Octobre 2012.
CFBR, Recommandations pour le dimensionnement des évacuateurs de crues de barrages, Juin 2013.

Remerciements GEOS Ingénieurs Conseils SA, Genève

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Upstream erosion at Piano Key Weirs

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[1]Laboratoire de constructions hydrauliques (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL)

Introduction

Piano Key Weirs (PKWs) are an inlet structure with high hydraulic performance under low heads. The utilization in rivers without a gated weirs next to the structure highlight the challenge about the sediment transport. This study focuses on the upstream erosion at PKWs.

Figure 1: Van Phong Dam, Vietnam

Experimental setup

- Systematic tests were performed in the LCH – Epfl laboratory in a channel of 4.5 meters length with a width of 0.65 and 0.63 meters following the PKW configurations (Figure 2).
- In total 23 tests were performed varying systematically 3 PKWs configurations (Figure 2), 2 sediments type (d_{50} = 1.80 and 6.90 mm) and 4 - 6 discharges (from 0.015 m^3/s to 0.090 m^3/s).
- The river bed was inserted horizontally upstream PKW up to the crest including inlet keys. Only free overfall conditions were considered and all tests were performed in clear water erosion conditions.

Figure 2: Experimental setup (left) and PKW configurations

Tests

The 23 tests were divided into 7 series (Equilibrium tests + Serie 1,2,3,4,5 and 6). Different photos were taken from different perspectives.

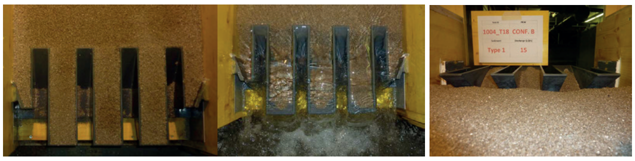


Figure 3: Test 18 - Starting conditions (left), during test (middle) and final conditions (right)

Rating curves tests

The rating curves for configurations A and B were measured at three different upstream fixed depth as $\mathbf{P}$, $\mathbf{P/2}$ and at the crest.

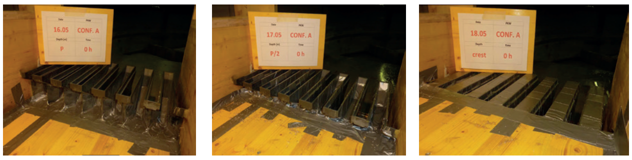


Figure 4: Rating curves tests: fixed level at P (left), at P/2 (middle) and at the crest (right)

Tests Results

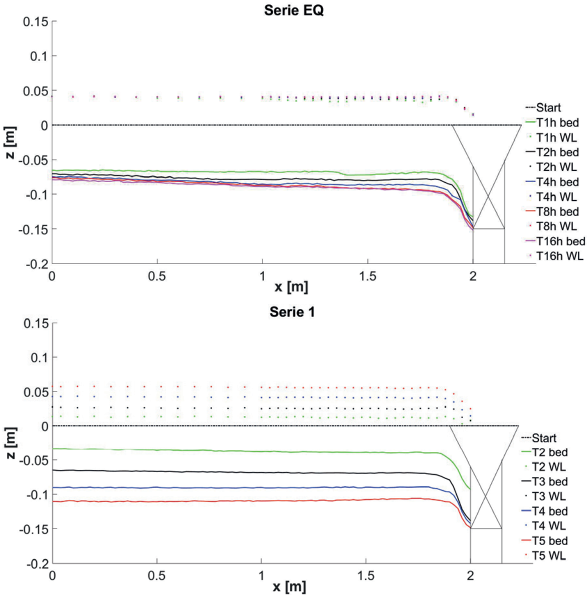


Figure 5: Bed topography (bed) and water level (WL) at the end of tests – Equilibrium tests and Serie 1

With the fine sediment the bed topography and the water surface at the end of the test were almost flat. For the coarse sediment with the discharge of 0.015 m^3/s and 0.030 m^3/s no completely erosion was observed.

Rating curves results

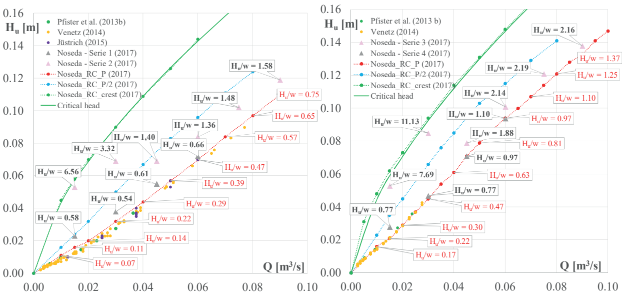


Figure 6: Rating curves results configuration A (left) and B (right): fixed level at P (red dotted line), at P/2 (blue dotted line) and at the crest (green dotted line)

Conclusions

- The ratio between the upstream head and the mean erosion $\mathbf{H_u/w}$ dominates the behavior of the rating curve and determines the increase of $\mathbf{H_u}$.
- The parapet wall plays a role of retention of sediments thus increasing $\mathbf{H_u}$.
- This study allowed highlighting the capacity of PKWs to flushing out the sediments from the inlet keys and that no deposition occurs upstream the structure. In addition, the rating curve of the PKW configuration was an important parameter that dominates the upstream hydraulic conditions.
- **In conclusion, the construction of this type of structure in rivers without a gated weir next to the structure could be considered as feasible.**

Versuchsanstalt für Wasserbau,
Hydrologie und Glaziologie

Supervisors: Prof. Dr. Robert M. Boes
Dr. Sameh A. Kantoush
Student: Eliott Odermatt

Networking of Reservoir Sediment Management Groups for Sustainable Water Resources in the River Basin Scale

Introduction

Although all rivers continuously transport sediment, only a small portion of the existing dam perform sustainable sediment management [Figure 1]. The consequence is a lost of storage capacity called sedimentation, along with a lost of benefits, e.g. supply for irrigation and freshwater, hydropower and flood protection.

Objectives

The main objective is to prepare the structure for a new database. Its objectives: *“Collect, share and provide information, principally in the form of datasets, about sediment management, reservoir sedimentation, their impacts, costs, and benefits for modellers, designers, and decision-makers to improve the sustainable management of water resources integrated on the basin scale.”*

Review of Existing Efforts

Fifteen existing efforts on dam and reservoir worldwide were reviewed [Table 1]. They differ in the information they provide [Figure 2], as well as on their type, dimension, access-limitation, and initiator entity. Not a single database actually provides information about sediment management, thus showing the need for a new database.

Name
World Register of Dams
Global Water Information System (dams)
Global Reservoir and Dam Database
National Performance of Dams Program
Reservoir Sedimentation Survey Database
Reservoir Sedimentation Information System
U.S. Geological Survey Sediment Data Portal
Global Data of Erosion and Sedimentation
Global Water Information System (rivers)
Hydrological data and maps (HydroSHEDS)
Dam Impacts on Rivers, Ecosystems and People
International Sediment Initiative
European Sediment Network
Sediment Management Network Group
Regional Sediment Management Program

Table 1: Reviewed efforts

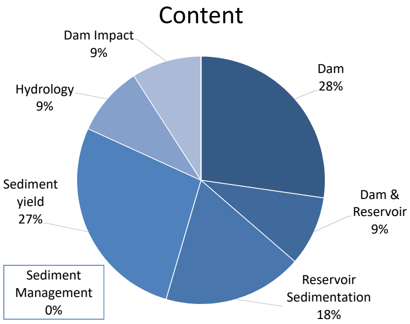
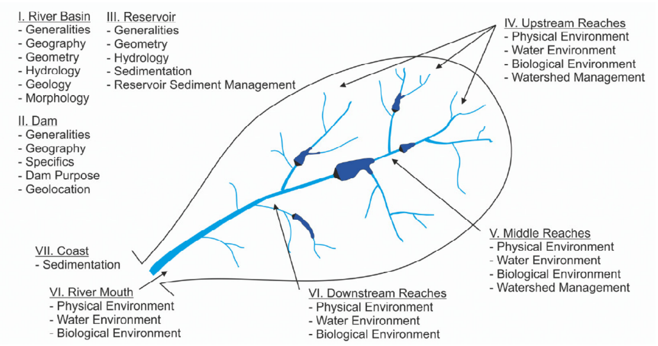


Figure 2: Content of reviewed existing databases

SDMNet Database Development

The developed Sediment and Dam Management Network (SDMNet) database uses the river basin as a key point. Eight zones were identified within the river basin, groups in each zones [Figure 3] and attributes in each group. In total, over 600 attributes were selected to fully describe the river basin, the sediment management and the impact on the environment.



I. River Basin
- Generalities
- Geography
- Geometry
- Hydrology
- Geology
- Morphology

II. Dam
- Generalities
- Geography
- Specifics
- Dam Purpose
- Geolocation

III. Reservoir
- Generalities
- Geometry
- Hydrology
- Sedimentation
- Reservoir Sediment Management

IV. Upstream Reaches
- Physical Environment
- Water Environment
- Biological Environment
- Watershed Management

V. Middle Reaches
- Physical Environment
- Water Environment
- Biological Environment
- Watershed Management

VI. Downstream Reaches
- Physical Environment
- Water Environment
- Biological Environment

VI. River Mouth
- Physical Environment
- Water Environment
- Biological Environment

VII. Coast
- Sedimentation

Figure 3: Zonation of the river basin and groups of attributes

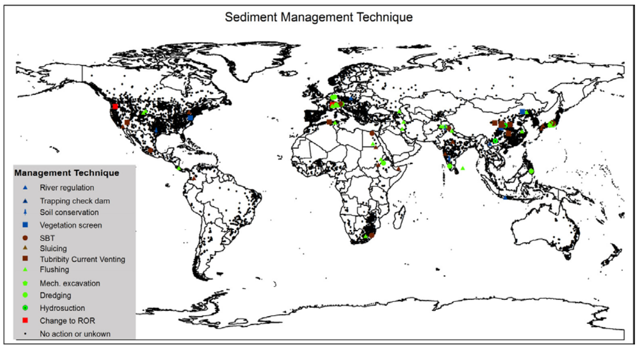


Figure 1: Sediment Management in the world [Data source: GRanD, GDAM]

Case Study: Kurobe River, Japan

The case study of Kurobe River, Japan, is studied to review the developed database structure and to provide a first content for the database. The scope of this case study is to provide a successful example of sediment management on the basin scale. There are 6 dams in the Kurobe river-basin. Dashidaira and Unazuki perform coordinated flushing and sluicing. The operation modus of the two small cascade dams Sennindani and Koyadaira was changed to run-of-river after they suffered severe sedimentation. Kurobe Dam is not managed from a sediment point of view, and no information could be found for Kitamata Dam [Figure 4].

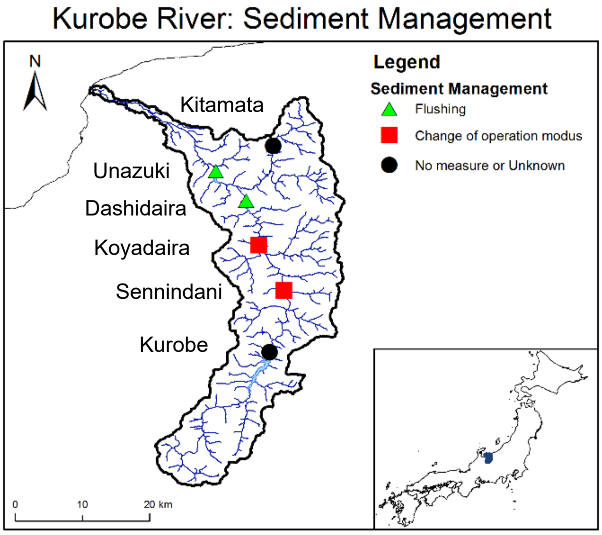


Figure 4: Dams and sediment management [data source: GRanD, NPDP, GDAM, ASTER]

Conclusion and Outlook

Within this project, the structure for the new SDMNet Database was prepared. The database will now be constructed by external consultants. Further, contributions from all over the world will be required to fill the database. To motivate SDMNet members to share this effort, it will be necessary to show them the possible benefits of both sediment management and the database.

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Exploring the hydropower potential of future ice-free glacier basins

Vanessa Round[1,2], Matthias Huss[2,3], Daniel Farinotti[2,1]

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(3)Department of Geosciences, University of Fribourg

Context and motivation

Glacier retreat is exposing **new landscapes** and **changing runoff** regimes in glaciated regions around the world. Newly exposed ice-free basins may provide **new locations for hydropower development**.

Increasing hydropower capacity is in line with global efforts to curb CO_2 emissions, and with the newly approved **Swiss Energy Strategy 2050**. New dams could also mitigate shifts in seasonal **water availability** [1] or potentially **hazardous new glacier lakes** [2].

Fig. 1 Switzerland has a long tradition of pioneering Hydropower development in high alpine, glaciated catchments (left: Abigna Dam, right: Griessee).

We develop a method to assess potential dam **storage volume, electricity production** and **feasibility** for each individual glacier location. We apply this to the European Alpine region as a validation before moving the analysis to glaciated regions globally.

Simulation of potential dams

Dam walls are simulated at the current terminus of each glacier
- Subglacial topography from global ice thickness model [3]
- Geometry optimized to minimize "dam-wall area / lake volume"
- Wall dimensions limited to 280 m height, 800 m length

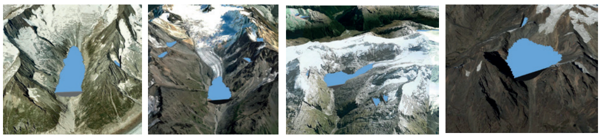


Fig. 2 Dams simulated in European Alps, the Caucasus, New Zealand and Peru

Potential energy production

Potential annual energy production for each site is calculated from projected catchment runoff and hydraulic head.
- Catchment runoff until 2100 from Global Glacier Evolution Model (GloGEM, [4]).
- Available hydraulic head generated from ASTER global elevation model (10% slope limit, 8km distance limit)

Site feasibility assessment

Technical factors
- Average catchment slope (potential for rock fall), global lithology.
- Reservoir fill time
- GloGEM modelled ice retreat: when will the basin be ice free?

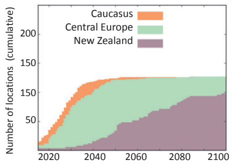
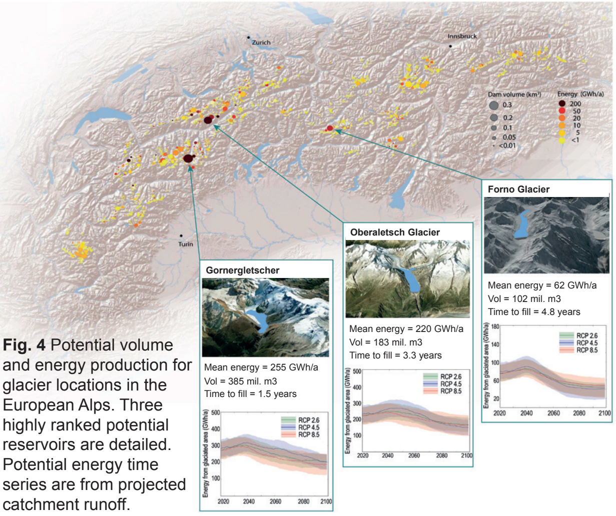


Fig. 3 When will the potential basins become ice-free?
The cumulative number of locations becoming ice-free are shown, for reservoir volumes larger than 10 mio. m^3, in three different regions.

Social and environmental factors
- Demand for electricity: population density, national statistics
- Density of endangered species
- UNESCO protected areas

Economic factors
- Weighted cost to benefit ratio
- Proximity to existing infrastructure

Potential in the European Alps



Gornergletscher
Mean energy = 255 GWh/a
Vol = 385 mil. m3
Time to fill = 1.5 years

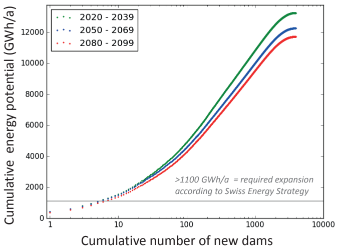
Oberaletsch Glacier
Mean energy = 220 GWh/a
Vol = 183 mil. m3
Time to fill = 3.3 years

Forno Glacier
Mean energy = 62 GWh/a
Vol = 102 mil. m3
Time to fill = 4.8 years

Fig. 4 Potential volume and energy production for glacier locations in the European Alps. Three highly ranked potential reservoirs are detailed. Potential energy time series are from projected catchment runoff.

Our automated methods for assessing potential reservoir volume and energy production for each glacier location reveal significant potential in the European Alpine region.
- >1000 GWh/a could be generated from the five largest potential locations (considering only immediate catchment runoff)
- The largest simulated dam volume exceeds 380 million m^3 (Gornergletscher), approaching the size of Grand Dixence.
- Many of the identified high potential sites correspond with previously recognized or existing dam locations.

Fig. 5 Cumulative annual energy generation from new dams in projected ice-free basins in the European Alps, over three time periods.
The 1100 GWh/a level indicates the additional production required to meet the Swiss Energy Strategy goals.



Outlook

The potential storage volume and energy production from future ice-free basins in the European Alps is significant. This study is being expanded to investigate the potential in glaciated regions globally. Aside from the physically possible reservoir volumes and energy production, feasibility depends highly on factors such demand for electricity, population density, site accessibility, cost-benefit ratio and technical, environmental and social risks. These are taken into account in the development of a feasibility framework.

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Hydropower potential at *Oberaletsch Glacier*

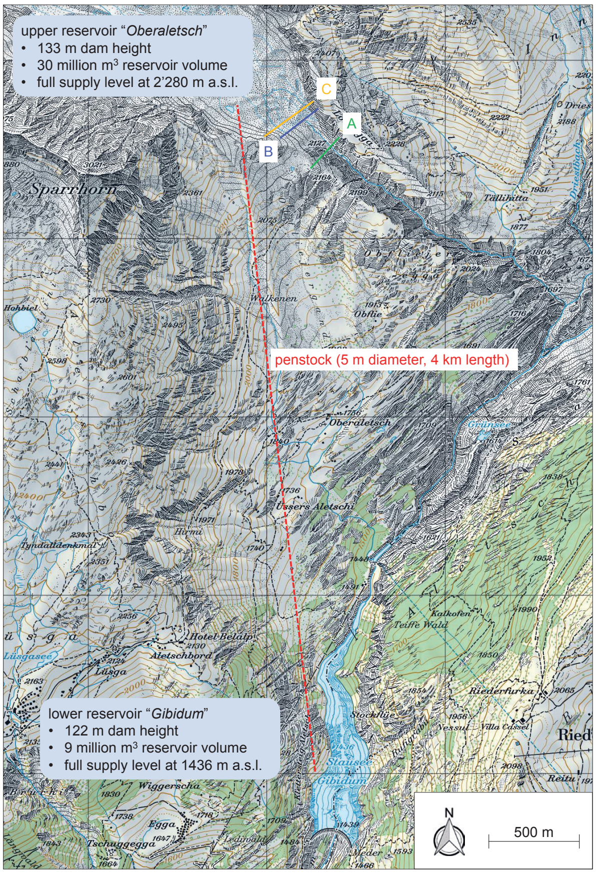
Romina Rulli, Daniel Ehrbar, Lukas Schmocker, Daniel Farinotti, Robert Boes – VAW ETH Zurich

Introduction

Hydropower shall be further exploited according to the new Swiss Energy Strategy 2050. The goal for 2035 is to achieve an annual domestic electricity production of 37’400 GWh . Due to glacier retreat, *Oberaletsch Glacier* might become a potential future site and a reservoir for hydropower production.

Current situation

Oberaletsch Glacier is located about 10 km north of the city of *Brig*, upstream of *Gibidum* reservoir (Fig. 1). On the one hand, geological boundary conditions are suitable for dam construction, as there is predominantly Aare granite present. On the other hand, the *Valais* is prone to earthquakes, which must be considered when assessing the dam type. A mean annual runoff volume of circa 60 hm^3 is estimated from 2020 to 2100 based on climate models.



upper reservoir “*Oberaletsch*”
- 133 m dam height
- 30 million m^3 reservoir volume
- full supply level at 2’280 m a.s.l.

penstock (5 m diameter, 4 km length)

lower reservoir “*Gibidum*”
- 122 m dam height
- 9 million m^3 reservoir volume
- full supply level at 1436 m a.s.l.

Fig. 1: Situation with potential dam locations and layout of the penstock [map: © swisstopo]

Oberaletsch Glacier is within the UNESCO World Heritage “Swiss Alps Jungfrau-Aletsch” and is well protected by the Federal Inventory of Landscapes and Natural Monuments of National Importance (BLN) 1706 “Bernese High Alps and Aletsch-Bietschhorn region”. The new Energy Law is game-changing for this project, because large-scale hydropower is of national interest. Protection of nature and use for the production of renewable energy will have an equal value, so it is no longer impossible to build a reservoir in a protected area.

Results

In a concept study, various types of hydropower plants – run-of-river, storage, and pumped storage – were examined. A pumped storage plant was finally chosen, due to its large technical potential and flexibility and the existence of a lower reservoir, i.e. the *Gibidum* reservoir. In a variation study, three dam locations (Fig. 1) were investigated. Furthermore, three dam types – rockfill dam, arch dam, and gravity dam – were analysed. It turned out that location “C” and an arch dam fit best to the given situation and geological boundary conditions.

Preliminary design study

The full supply level is at 2’280 m a.s.l. The arch dam is 133 m high (Fig. 2) and the reservoir volume is 30 million m^3. Four 2-nozzle Pelton turbines are installed 830 m below the full supply level, nearby *Gibidum* reservoir. Due to topographical constraints, a single headrace tunnel with a diameter of 5 m is planned, without surge chamber (Fig. 1). A chute with ski-jump serves as spillway. Given a design discharge of 69 m^3/s, an installed capacity of 470 MW can be achieved. Despite the glaciated catchment and highly erodible sediments, infill time (time, until the reservoir is completely filled with sediment) is circa 700 years. The costs of this project have been estimated to 580 Million CHF.

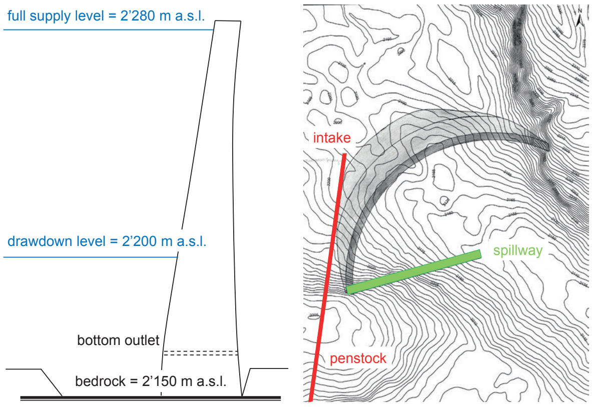


Fig. 2: (left) cross section of the arch dam; (right) situation with arch dam, spillway, and penstock

Conclusions

A reservoir at *Oberaletsch Glacier* with an annual electricity production of up to 1’400 GWh (including pumped storage operation) would contribute substantially to Energy Strategy 2050. Together with *Gibidum* reservoir, a pumped storage plant could be realized. Next planning steps require detailed geological surveys at the dam location.

Acknowledgements

This project is financially supported by the Swiss National Science Foundation (SNSF) within the National Research Programme 70 “Energy Turnaround” Project No. 153927. The close collaboration of Alpiq is gratefully acknowledged.

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Multipurpose Hydropower Plant on Alpine Rhine River

Katharina Sperger, Julian Meister, Robert Boes – VAW, ETHZ

Motivation and Objectives

Ever since storage power plants have started operation in the Alpine Rhine catchment, large and fast water level fluctuations (hydropeaking) occur in the Alpine Rhine. Furthermore, there is a flood protection deficit starting from a 100-year flood along the international river section (Michor et al., 2005). In this work, the construction of a river power plant was investigated, which offers a damping possibility for both hydropeaking and flood discharge at the Alpine Rhine and in addition exploits the hydropower potential of the region.

Concept study

By means of a qualitative cost-benefit analysis, a diversion river power plant in Maienfeld / Bad Ragaz was defined as the best concept. For the best variant, the water level is impounded with a weir to 513 m a.s.l.. A frontal intake and an open headrace channel guide the water to the power house (Fig. 1). Two bulb turbines with a design discharge of 100 m^3/s each produce around 110 GWh of electricity per year, resulting in production costs of 9.7 Rp / kWh.

The retention basin located downstream of the power house dampens hydropeaking during the winter months, resulting in water level fluctuations of up to 6 m in the retention basin. In summer, the basin is kept at a minimum water level and the power plant can be operated at full head (15.25 m). During flood events, the basin can be drawn down in advance and then exhibits 1.2 million m^3 of flood retention volume.

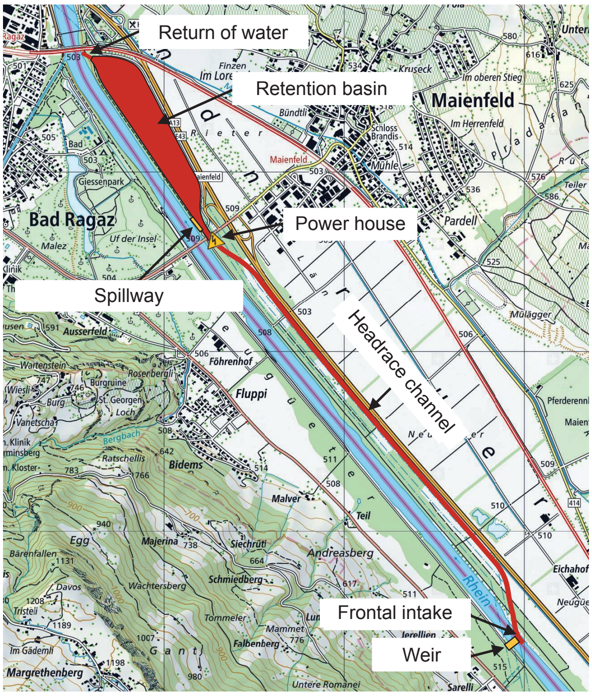

Fig. 1: Situation of the planned power plant (swisstopo, 2017)

Hydropeaking mitigation

The retention capacity of the basin was examined in a hydraulic model with the software *HEC-RAS* (Fig. 2). In the best variant, the ratio of the discharges between down- and upsurge can be reduced to below 1:2.

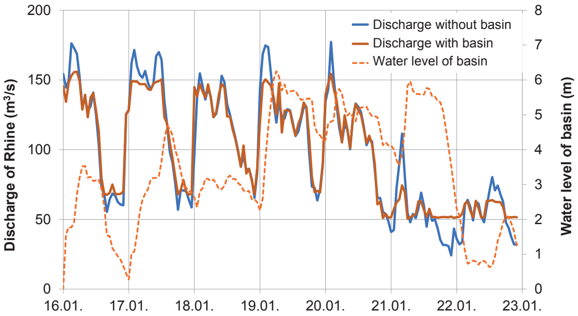

Fig. 2: Discharge of Rhine with and without (BAFU, 2017) retention basin and water level in the retention basin during a characteristic winter week in 2017

The retention basin guarantees that the requirements regarding hydropeaking for the assessment profile AP1 are met (Schälchli et al., 2012). This results in a significant improvement for ecology and bed load equilibrium (Table 1). In combination with further measures, the severe impairment can be minimized and an important contribution to a more near-natural Alpine Rhine River can be achieved.

Table 1: Requirement profiles AP1 to AP4 at the Alpine Rhine between the two tributaries Landquart and Ill River (Schälchli et al., 2012). The damping effect achieved by the retention basin is marked in green.

	Upsurge	Downsurge	Amplitude	Surge increase	Surge decrease	Down- / up-surge ratio
	[m^3/s]	[m^3/s]	[m^3/s]	[m^3/s/min]	[m^3/s/min]	[-]
Actual state	160 - 200	60 - 70	90 - 130	max. 0.7	max. 0.8	1:2.3 – 1:3.3
AP1	160	79	81	0.7	0.25	1 : 2.0
AP2	140	95	45	0.5	0.2	1 : 1.5
AP3	125	106	19	0.3	0.15	1 : 1.2
AP4	116	116	0	0.2	0.1	1 : 1

Conclusion

The projected river power plant contribute significantly to the exploitation of the hydropower potential (Fig. 3) as well as the mitigation of hydropeaking on the Alpine Rhine.
In addition, the flood safety for downstream regions can be improved by an optimum regulation of the retention basin.

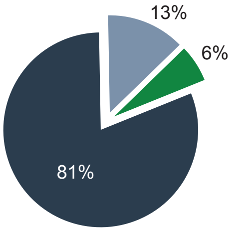

Fig. 3: Exploited hydropower potential of the power plant (green). Light blue: Installed potential at alpine rhine; Dark blue: unexploited potential (Böhl et al., 2003)

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Stilling basin performance downstream of stepped spillways

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Introduction

In the last three decades, stepped spillways have gained a significant popularity due to the advancements in roller compacted concrete (RCC) construction technique. A key feature of a stepped spillway, when compared to the classical (smooth) spillway, is the significant energy dissipation along the chute. As a result, energy dissipators can be reduced in size. Stilling basins are typically applied as outlet dissipators for stepped chutes.

Figure 1: Pedrógão dam, Portugal (Photo: Ivan Stojnić)

During the 1960's and the 1970's, based on model and prototype studies, several standard stilling basin designs have been developed (USBR, SAF, PWD, WEC etc.). All these standardized basin types have been developed for smooth invert chutes.
The hydraulic behaviour of standard stilling basins (in particular USBR type) in combination with stepped spillways have been tested in some experimental studies (Cardoso el al. 2007, Frizell et al. 2009, 2016, Meireles et al. 2010, Bung el al. 2012, Frizell and Svoboda 2012). However, no systematic studies have been conducted so far providing general design guidelines for stilling basins downstream of stepped chutes.

Objectives

The aim of this study is to systematically investigate the flow features and the overall performance of stilling basins downstream of stepped spillways. The main research questions can be summarized as:

- What is the effect of the self-aerated or non-aerated stepped/smooth chute inflow on the efficiency of the adjacent stilling basin?
- What is the effect of the self-aerated or non-aerated stepped/smooth chute inflow on the dynamic bottom pressures of the stilling basin?
- What are the dimensions (length, baffle block size, etc.) necessary to achieve an efficient operation mode of stilling basins downstream of a stepped chute? Do these differ from the standard types as proposed by USBR?

Research methodology

For this study, a physical model will be used to investigate stilling basin performance downstream of stepped spillways. The facility that was designed and constructed in the facilities of LCH consists of (Figure 2, 3): jet-box, 0.5 m wide and 6.0 m long chute with adjustable slope and 0.5 m wide, 6.0 m long stilling basin.

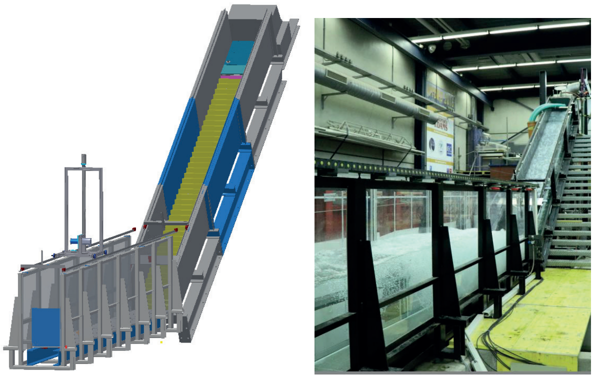

Figure 2: Schematic representation (left) and downstream view of experimental facility(right) at LCH

Parameters and measurements

In order to thoroughly investigate its performance, the following parameters will be systematically varied:

- Chute slope
- Step height (including a smooth chute)
- Discharge
- Stilling basin geometry (basin length, appurtenances geometry - chute blocks, baffle blocks, end sill etc.)
- Tailwater depth

In each test scenario detailed flow measurements will be conducted throughout the spillway. Measurements will be mainly focused on:

- Flow properties at the toe of the chute – air concentration, velocity, flow depths
- Air concentration and velocity distribution in the hydraulic jump
- Flow depths along hydraulic jump
- Roller and jump length
- Dynamic pressures along the stilling basin invert

Figure 3: Side view of experimental facility in operation.

Output

This research is expected to provide a deeper understanding of stilling basin performance under aerated and turbulent inflows as typically produced on stepped chutes. The most important output will be new design recommendations for stilling basins downstream of stepped chutes.

Acknowledgments

This research project is developed in the scope of the Ph.D. Thesis by Ivan Stojnić under the joint IST-EPFL doctoral program H2Doc. It is funded by the Portuguese Foundation for Science and Technology and LCH-EPFL.

«The Future of Swiss Hydropower» project presents:

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Will the path toward sustainability kill Swiss hydropower?

Sustainability assessment of 4 options for one hydropower project in Val d'Ambra, Ticino

Many hydropower concessions are coming to an end in the Swiss Alps, opening a window of opportunity for new alternatives.

However, choices made today will most likely shape the face of the Swiss mountains for the next 80 years...

For the renewal of the **Hydropower plant of Val d'Ambra** **4 alternatives** have been considered

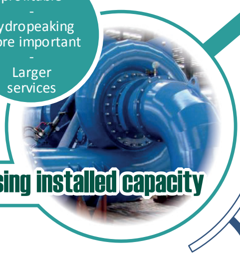
Plant characteristics

Installed capacity: 50MW
Expected production: 111 GWh/yr
Maximal height of the dam: 86m
Estimated water fees: 240'000 CHF/yr

A Statu quo

Reference alternative serves as a basis for the other options

B Increasing installed capacity



More profitable
-
Hydropeaking more important
-
Larger services

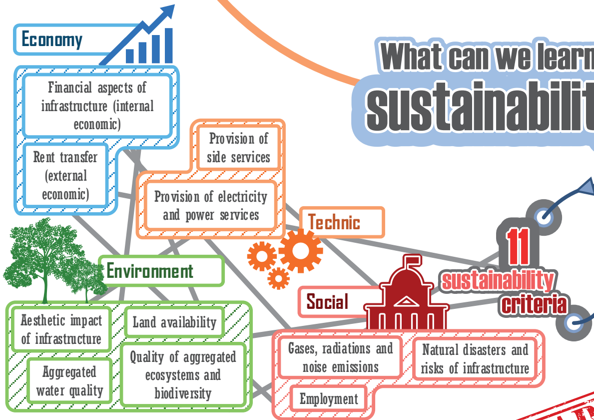
C Abandoning facility

Cheapest option
-
Visual impact still existant
-
No services

D Decommissioning facility

Costliest option
-
Back to natural state
-
No services

What can we learn from a sustainability perspective?



11 sustainability criteria

Economy
- Financial aspects of infrastructure (internal economic)
- Rent transfer (external economic)

Technic
- Provision of side services
- Provision of electricity and power services

Environment
- Aesthetic impact of infrastructure
- Land availability
- Aggregated water quality
- Quality of aggregated ecosystems and biodiversity

Social
- Gases, radiations and noise emissions
- Natural disasters and risks of infrastructure
- Employment

Method of analysis

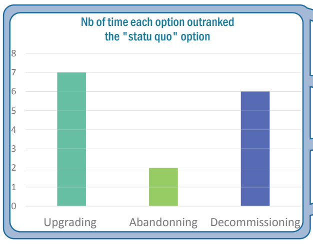
Multiple Criteria Decision Analysis (SAW)

1. Assignement of value scores to criteria
2. Assignement of weights between criteria
3. Aggregation of scores and weights to guide decision-makers

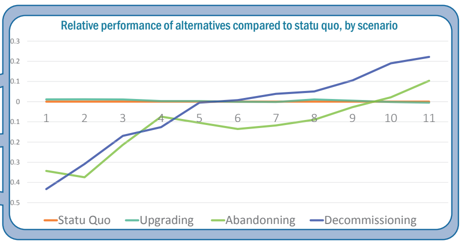
UNCERTAINTY

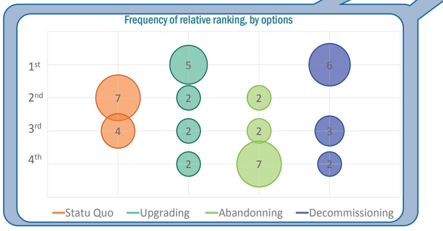
- Criteria perception (positive or negative)
- Values considered for projected impacts
- Standarized values
- Number of dimensions, criteria and indicators considered
- Weighting attributed to criteria

EARLY! RESULTS


Nb of time each option outranked the "statu quo" option

1. **Statu quo** appears always as either second (7) or third (4), but is never the worst or best alternative
2. **Abandonning** is never the best option, and is most of the time the worst one (7)
3. Indeed, the best options are always either **Decommissioning** (6) or **Upgrading** (5)
4. However, **Upgrading** outscores **Statu quo** more often (7) than **Decommissioning** does (6)
5. Relatively, **Upgrading** always has a close scores to **Statu quo**, compared to the other alternatives


Relative performance of alternatives compared to statu quo, by scenario


Frequency of relative ranking, by options

CONCLUSION

What option to choose?

The results can show the **most robust option**, the one that **performs the best** in the scenario α, or the one having the **highest average score**...

However, it is important to keep in mind that the role of MCDA **is not to take a decision**, but to **provide** the decision-makers with **relevant information.**

How to limit uncertainty?

Increase the quality of information regarding the **expected impacts!**

However, control over this aspect is usually very limited...

Then, increase the **availability** of information regarding the **weighting** and **perception** of concerned people in order to **give sense to the predicted impacts.**

There a better control is possible! **Go and meet those people!**

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Floating Debris at Dam Spillways: Hazard assessment and Engineering Measures

Working Group - Swiss Committee on Dams

Motivation

Flood events in mountainous areas may entrain and transport large amounts of floating debris or large wood (LW). LW may endanger the save operation of dam spillways, as it can result in blocking of the spillway cross section. Already partial blocking of the spillway can decrease the discharge capacity considerably. Due to the resulting backwater rise, the freeboard requirement may not be guaranteed and in an extreme case, uncontrolled overtopping of the dam may occur. The blocking of the Palagnedra spillway, Switzerland, during the flood event in 1978 (Fig. 1) is a prime example demonstrating the hazard potential of transported LW.

Fig 1: Blocking of spillway at Palagnedra Dam in 1978 (Photo: Ofima SA).

Swiss Survey

Although LW transport during flood events is a major threat, limited knowledge is currently available on the interaction between LW and the spillway and the magnitude of a possible backwater rise. No general guidelines on LW management at spillways is currently available. Therefore, the Swiss Committee on Dams established a working group to summarize international guidelines and best practice on LW and floating debris at dam spillways.

A questionnaire was distributed to 60 Swiss hydropower plant (HPP) owners to collect information regarding LW occurrence and problems at spillways. The results demonstrate that LW occurs at approx. 90% of the HPPs and 17% of the HPPs already experienced problems or damages due to LW (Fig.2) .

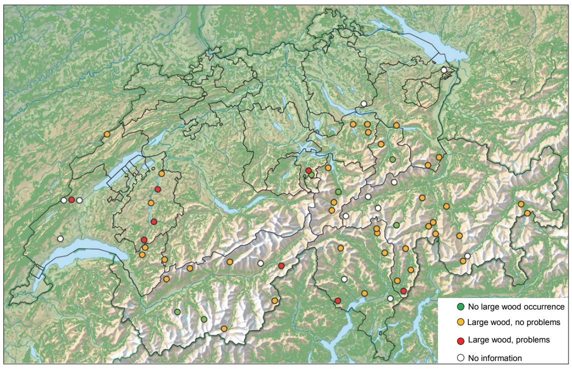

Fig 2: Results of Swiss survey on occurrence and problems regarding large wood at dam spillways.

Hazard assessment

The hazard assessment was summarized in a diagram (Fig. 3) that includes the following main steps:

1. Determination of external loads (e.g. flood discharges, LW potential) and both spillway and dam design (e.g. type, dimensions, freebord, hydraulics)
2. Check guidelines regarding minimal required dimensions of spillway and determine blocking probability
3. Assessment of hazard potential due to spillway blocking
4. Decision if hazard due to floating debris is low or high
5. Develop measures to minimize the potential hazard

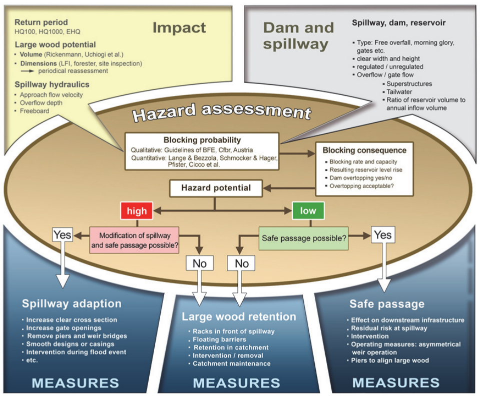

Fig 3: Hazard assessment diagram for floating debris and LW at dam spillways.

Engineering Measures

If the hazard potential and especially the blocking probability are small, large wood may be conveyed through the spillway. If the hazard potential is high, two main measures may be applied to decrease it:

1. Guarantee safe spillway passage of the large wood with spillway adaptations: Increase clear cross section or gate openings, remove piers and weir bridges, use smooth designs or casings, etc.
2. Retain large wood upstream: Check dams and racks in the catchment, floating barriers in calm water sections of the reservoir, racks in front of the spillway, etc.

Some examples are given in Figure 4.

Fig 4: (a) New clear spillway with displaced weir bridge at Palagnedra Dam, Switzerland (Photo: polier.ch), (b) Floating debris barriers at Lake Brienz, Switzerland (Photo: Swiss Airforce), (c) Rack in front of spillway of Thurnberg Reservoir, Austria (Photo: bmlfuw)

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