Modelling and Analysis of Hydropeaking in Alpine Catchments equipped with Complex Hydropower Schemes

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Abstract: *High-head storage hydropower schemes in Alpine areas are required to produce peak energy and to regulate electricity grids. Nevertheless the unsteady turbine operations induce hydropeaking in the river downstream of the powerhouse. The developed hydrological-hydraulic model can simulate glacier melt, snow pack constitution and melt, soil infiltration and run-off as well as hydraulic structures and hydropower schemes. The operation of complex plants and the resulting ecological impact are generated. The modelling process is explained for the upper Aare River catchment in Switzerland, containing the Oberhasli hydropower scheme. For a simplified catchment area, systematic simulations define the influence of meteorologic, hydrologic and morphological parameters on the river flow regime for natural as well as operated catchments. In a second step, the model's ability in reproducing hydropeaking at the outlet of the upper Aare River catchment is tested. Finally operation rules induced by the dynamic electricity market are simulated.*

Keywords: *Hydropeaking, hydrological modelling, Alpine catchment, storage hydropower schemes.*

1. INTRODUCTION

In Alpine countries, high-head storage hydropower plants contribute significantly to electricity production. For example in Switzerland, 60% of the demand is covered by hydropower plants. Reservoirs at high altitudes can store rain, snow melt and glacier melt, collecting it during summer in order to use it in winter. High-head storage hydropower plants concentrate their turbine operations during periods of high energy demand. The sudden opening and closing of the turbines produces highly unsteady flow conditions in the river downstream of the powerhouse outlet. The natural flow regime of the river is considerably influenced by this so called hydropeaking and can result in degradation of the river eco-system.

The article presents the development and use of the hydrological-hydraulic model, which allows simulating the operation of storage hydropower schemes for different scenarios. The parametric study allows a sensitivity analysis of the meteorologic, hydrologic and economic parameters. The conclusions are applied for the upper Aare River catchment in Switzerland (Figure 1a), an Alpine river strongly influenced by hydropeaking.

1.1. Effects of hydropeaking

Hydropeaking has an influence on almost all living organisms depending on the river eco-system (Pellaud, 2007; Harby *et al.*, 2010). The negative effects have been known for a long time (Vibert, 1939) on benthic macroinvertebrates, fish, periphyton and moss, aquatic macrophytes and riverbank vegetation. Literature studies (Baumann *et al.*, 2005) confirm the situation of macro-invertebrates driven ashore due to rapid water level fall or an increase of catastrophic drift during sudden increases in discharge, water levels and flow velocities. Biomass and richness of species are diminishing. A decrease of the biomass and a change in abundance and composition of adult fish have been reported in different studies (Pellaud, 2007). In addition, depending on river morphology drift and stranding endanger juvenile fish (Halleraker *et al.*, 2003). The natural reproduction of fish can be disturbed or completely hindered (Baumann & Klaus, 2003). Despite an increasing knowledge of the interactions between hydropeaking and ecology, it is currently still difficult to predict and quantify the biotic responses to hydropeaking.

1.2. Hydraulic and ecological rating

In a river cross section, hydropeaking is characterized by frequent changes between minimum and maximum flow levels. The amplitude of the variation depends on the maximum and minimum discharge as well as on the river morphology which includes the cross-sectional shape and backwater effects. In a river reach, hydropeaking creates a surge wave, which propagates downstream. Propagation and attenuation of these waves are influenced by the channel slope and roughness (Favre, 1935) as well as the river morphology (Stranner, 1996). The duration of the hydropeaking impulse is an additional parameter influencing the flow conditions. It is defined as the duration of the turbine operation. For long durations of impulses and channelized rivers, hydropeaking can be considered as the transition between two steady flow conditions. For shorter impulses and under complex conditions, hydropeaking produces increasingly dynamic effects.

Several hydraulic indicators (Table 1) can be used to quantify hydropeaking. For comparison of different scenarios as well as overall analysis these parameters are useful. Local morphology and habitat characteristics have to be taken into account for the full impact evaluation. For the upper Aare River, the ecological rating will contain a 2D hydraulic model for characteristic river reaches and a fuzzy logic approach (Schneider *et al.*, 2010), based on data of field measurements. Biologists provide knowledge and understanding of the impact of hydropeaking on the ecology of Alpine rivers. Discharge time series generated by the hydrological model can then be ecologically rated.

Table 1: Parameters and deduced indicators for characterizing hydropeaking (VAW-LCH, 2006)

Basic parameters		Defined parameters		Deduced inicators	
$Q(t,x)$	Discharge	Q_{max}	maximal daily discharge	Q_{max}/Q_{min}	drawdown range
		Q_{min}	minimal daily discharge	$\Delta Q = Q_{max} - Q_{min}$	drawdown difference
		Q_{ave}	average daily discharge	$\Delta Q/Q_{ave}$	
		MQ	average annual discharge	Q_{max}/MQ	
		dQ/dt	change of discharge rate	dQ/dt distribution	
$P(t,x)$	Water level	P_{max}	maximal daily flow level		
		P_{min}	minimal daily flow level	$\Delta P = P_{max} - P_{min}$	flow level difference
		dP/dt	water level variation rate	dP/dt distribution	

2. MODELLING APPROACH

To evaluate the performance of the hydrological model for simulating flows, the model of the upper Aare River catchment is set up and calibrated with real datasets.

2.1. Upper Aare River catchment

The upper Aare River has its source at the glaciers of Unteraar and Oberaar at the altitude of 2000 m a.s.l. and flows nowadays through the Oberaar, Grimsel and Räterichsboden reservoirs, in which the main part of the water is temporally stored (total retention volume of 209 Mm^3 in the reservoirs) before being turbined in the power plants of Grimsel, Handeck and Innertkirchen. In Innertkirchen the water is given back to the Aare River immediately downstream of the confluence with the Gadmerwasser, the river draining the eastern part of the catchment area. After the Aare Gorge the Aare River reaches the main valley of Meiringen and enters Lake Brienz at Brienzwiler. The surface of the upper Aare River basin is 554 km^2, where 21% was covered by glaciers in 2003. The hydrologic regime of the river is therefore glacial. The average annual discharge is 35 m^3/s.

At the end of the 19th century, the area of the Grimsel and Sustenpass was recognized as particularly appropriate for hydropower production. Heavy rainfall rates, large retention areas, solid granitic underground as well as substantial slopes provide optimal conditions for a hydropower storage scheme. The first concrete dams were built by the *Kraftwerke Oberhasli AG* (KWO) between 1925 and

1932. Since then, a complex scheme with nine power plants and eight reservoirs has been constructed and utilises 60% of the upper Aare River catchment (Figure 1a).

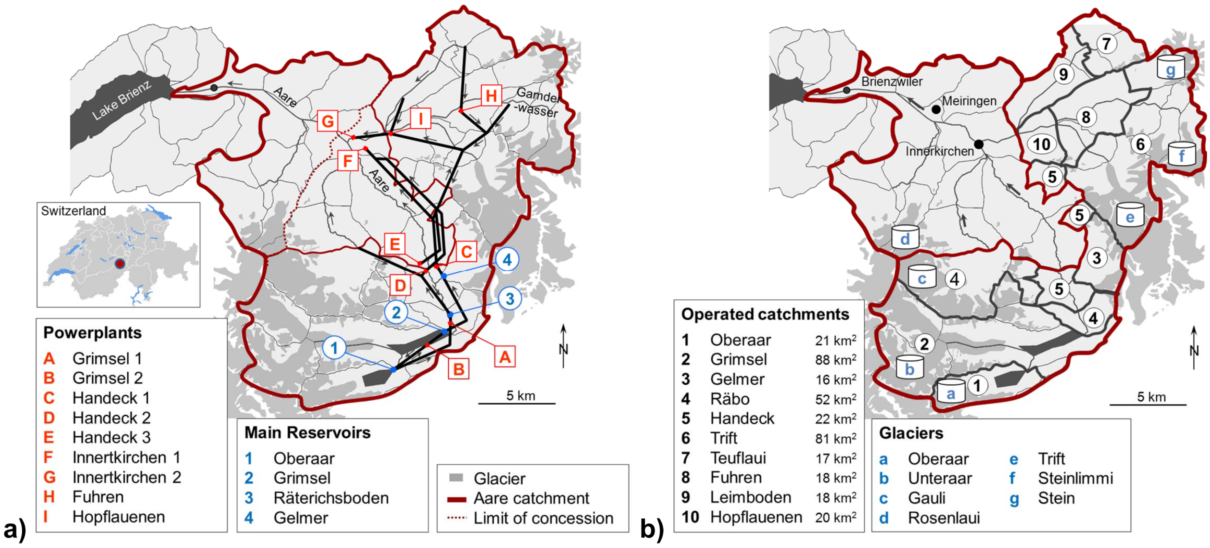

Figure 1 Upper Aare River catchment and implemented Oberhasli hydropower scheme (a) with operated sub-catchments and glaciers (b)

2.2. Hydrological model

For run-off estimations in catchment areas, production and routing of flow are calculated by numerical models. The semi-distributed conceptual code *Routing System* (García Hernández *et al.*, 2007) is appropriate for hydrologic forecasting in high mountainous catchment areas. It is based on a conceptual glacio-hydrological model (Schaefli, 2005). Tri-dimensional rainfall, temperature and evapotranspiration distributions are used for simulating the hydrological processes. The model is able to simulate glacier melt, snow pack constitution and melt, soil infiltration and run-off. The advantage of this object-oriented modelling tool is the integration of flood routing in rivers as well as hydraulic structures such as water intakes, water transfer tunnels, reservoirs with water releasing structures as well as powerhouses. It was successfully applied for several Alpine catchment areas in Switzerland, e.g. for the Rhone and Aare Rivers (Bieri *et al.*, 2010).

An altimetric temperature gradient is considered by subdividing each sub-basin into elevation bands, which allows segregating rainfall and snowfall. In a virtual station located at the centre of gravity of each band, meteorological input data is generated from the gauging stations in the vicinity by a radius defined influence zone. A catchment is simulated using four models: glacier, snow, infiltration (GR3) and surface run-off (SWMM). Depending on the presence of glaciers, two types of sub-basins are modelled. In Alpine regions, evapotranspiration (ETP) can generally be neglected.

The glacier sub-basin (Figure 2a) is composed of two models: snow and glacier. The snow model simulates the evolution of snow pack (melt and accumulation) according to temperature T and precipitation P and creates an equivalent precipitation P_{eq}. The latter is inserted into the glacier model with snow height H_N and temperature T. In the glacier model, equivalent precipitation influences the linear snow reservoir R_N and produces the outflow Q_{NGL} of the sub-catchment. Moreover, the sub-model of glacier melt shows an outflow when the snow height is equal to zero. This glacier flow P_{eqGL} enters the linear glacier reservoir R_{GL} and flow Q_{GL} results at the outlet of the sub-catchment. The sum of Q_{NGL} and Q_{GL} is the total outflow of the glacier sub-basin Q_{tot}.

In the non-glacier sub-basin (Figure 2b), three models – snow, infiltration and run-off – are used. The snow model is the same as in the glacier part, thus providing an equivalent precipitation P_{eq}, which is used as input for the infiltration model GR3. GR3 separates it into base flow Q_{base} and net intensity of precipitation i_{net}. This net rain intensity is transferred to the run-off model SWMM where it is routed. The total outflow Q_s of the glacier band is the sum of base flow Q_{base} and run-off Q_r.

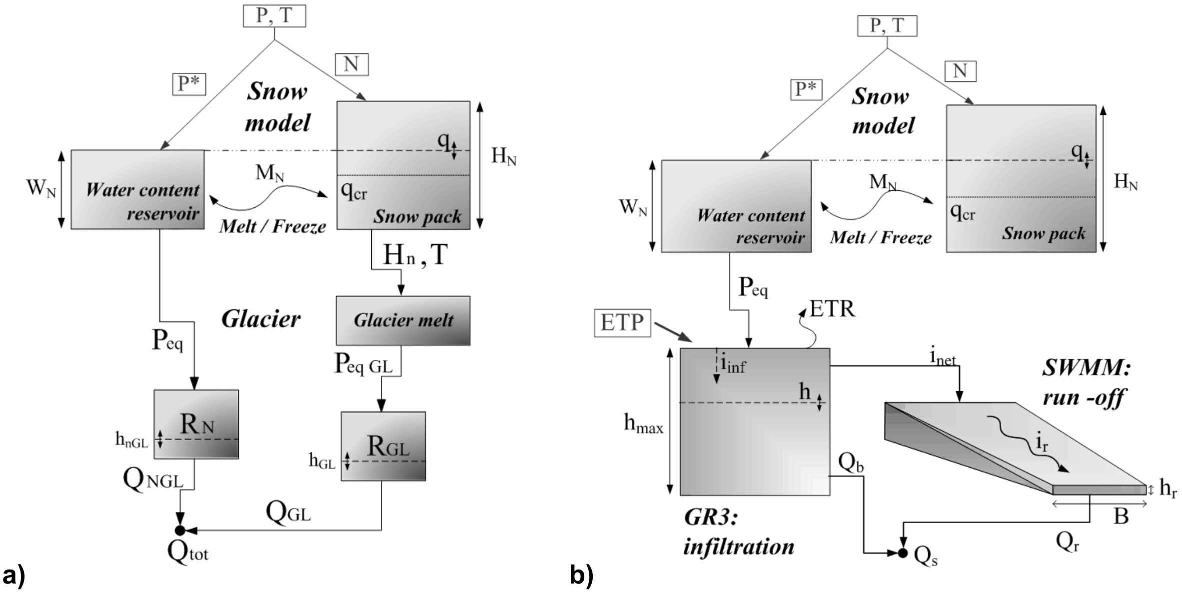

Figure 2 Modelling of glacier sub-basin (a) and of non-glacier sub-basin (b)

2.3. Data

For the simulations several input datasets are needed. The meteorological data are available from the Swiss Federal Office of Meteorology and Climatology. On the one hand, temperature and rainfall data are collected every ten minutes by an automatic monitoring network (ANETZ) all over Switzerland. On the other hand, a large number of gauging stations (NIME) measure the daily rainfall. Five stations of the first type and nine of the second are used as input data points in and around the upper Aare River catchment (Figure 4). The discharge is measured every ten minutes on the Aare River in Brienzwiler by the Swiss Federal Office of Environment (BAFU) (Figure 1b). The KWO made available the hydraulic characteristics of the hydropower scheme, operation rules and historical data from the last 30 years of operation. The daily datasets tallow calculation of the inflow of the ten sub-catchments operated by KWO (Figure 1b). For the year 2005 data was collected every 10 minutes.

2.4. Calibration

For the spatial distribution of the meteorological variables the method of Shepard was applied. Precipitation and temperature for a given elevation band are obtained by weighting the data of the real stations in the influence zone according to their inverse square distance to the virtual station of the band. This method has been extended to take into account the effect of altitude by a constant altimetric gradient.

For large catchment areas with multiple elevation bands, the same values for the eight calibration parameters (A_n, A_{GL}, K_N, K_{GL} for a glacier band and A_n, h_{max}, k, K_s for a non-glacier band) are adopted for predefined sub-catchments. The calibration process follows the hydrological cycle, allowing an independent calibration of the key parameters. The simulation period starts in October, because snow-pack is built-up during autumn and winter. The snow degree-day parameter A_n, which mainly influences the river run-off from February to June, is first calibrated. The degree-day glacier melt coefficient A_{GL}, the coefficient of linear glacier reservoir K_{GL} and the release coefficient of linear snow reservoir K_N influence summer run-off, when the snow is melting in the glacier elevation bands. The base flow depends on the infiltration of snowmelt and rainfall. The capacity h_{max} and the release coefficient of reservoir infiltration k are then calibrated. Finally the Strickler coefficient K_s, mainly influencing the flood hydrographs, is defined.

The catchment area of the Aare River upstream Lake Brienz was modelled for the configuration of 2003. The 41 sub-catchments are divided in 96 glacial and 243 non glacial elevation bands. The model was then pre-calibrated over five 15 month periods (2001-2005) for a one hour time step continuous simulation by using meteorological, hydrologic and exploitation datasets. The hydrologic parameters of the ten sub-catchments operated by KWO (Figure 1b) were optimised independently. The natural Aare River catchment was calibrated by data from the gauging station of BAFU, generating the same volume for a Nash coefficient of 0.86. The results, shown in section 4, reveal the importance of glacier melt, which highlight the need for the development of a specific tool taking into account its effect for future long time scenarios.

3. PARAMETRIC STUDY

The goal of the parametric study is the analysis of the influence of meteorologic, hydrologic and morphological parameters on the flow regime in the river for natural as well as operated catchment areas by an extraction of a calibrated sub-model.

3.1. Model

The model contains an Alpine catchment like the upper Aare River catchment, but five times smaller. Three identic sub-catchments of 36 km^2 each are situated between 500 and 4'000 m a.s.l. (Figure 3). The six highest bands are covered by glacier (totally 17% glaciated). The three sub-catchment areas are linked by the main river reaches 1, 2 and 3, with identic morphologic characteristics. The calibration parameters were taken from the upper Aare River model, from the lake Grimsel catchment for the higher part and the Brienzwiler catchment for the lower part, leading to a mean annual discharge of 6 m^3/s.

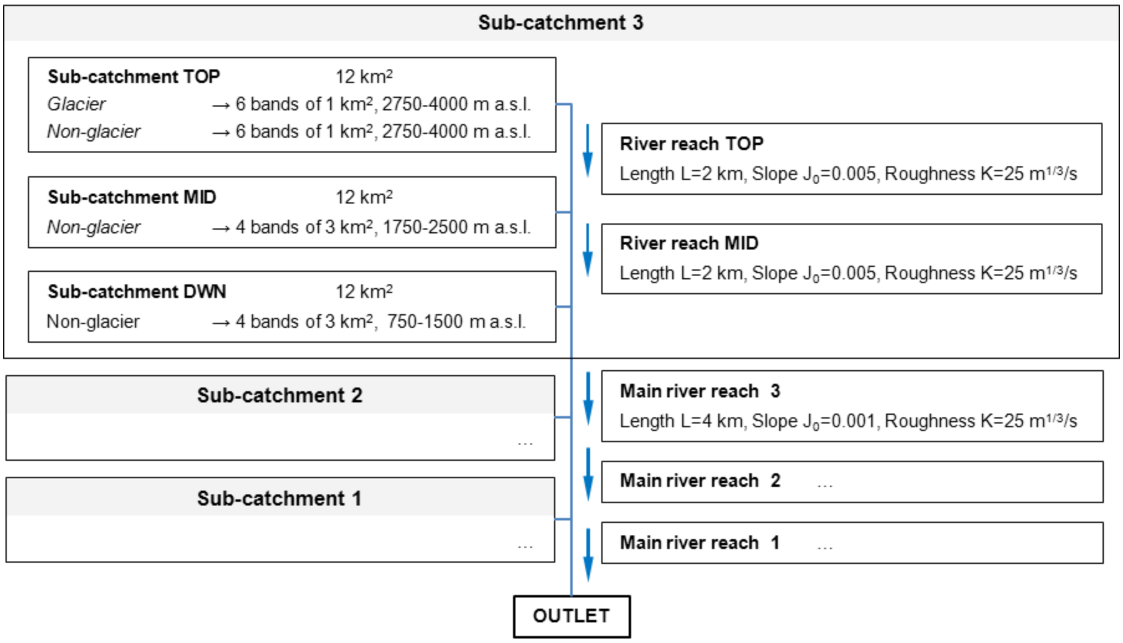

Figure 3 Model for parametric study with main hydrologic and morphologic parameters

An autonomous turbining tool is used for simulating the operation of the hydropower scheme (Figure 4). This tool is implemented at the outlet of a sub-catchment. The priority driving parameter is the electricity demand. When the electricity price of the market is higher than the cost price, turbining starts. For a seasonal water transfer, the whole reservoir volume should be used. The model tries to follow a preliminary defined target level curve. When inflow becomes too important compared to available storage volume, turbining for flood evacuation starts. The hydrologic characteristics of the sub-catchments allow for a reservoir volume of 25 Mm^3 and a turbining capacity of 15 m^3/s a seasonal exploitation. Other combinations have also been tested.

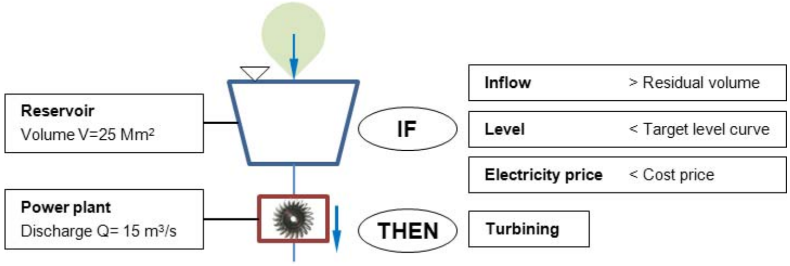

Figure 4 Autonomous turbining tool

3.2. Simulations

The year 2005 is chosen as reference, due to data availability. The simulations are run for a 15 month period at a ten minute time step, by using rainfall and temperature datasets from Grimsel ANETZ station and the electricity prices from the European Energy Exchange (EEX). Several scenarios are simulated for the natural and the operated catchment, by using the same input data and the identic hydrologic characteristics for all of the three sub-catchments:

- *Position*: The power plant generally operates sub-catchment 3 (SC 3). The plants at the outlets of sub- catchment 1 (SC 1) and 2 (SC 2) are also simulated.
- *Glacier*: The impact of the glacier is analysed for different surfaces of the glacier bands (GB). The total surface of the sub-catchments does not change.
- *Climate*: The influence of increasing or decreasing precipitation is tested by an overall factor between -20% and +20%. Several climate change scenarios predict global warming. Overall temperature was increased by +0.5°C, +1.0°C and +1.5°C.
- *Morphology*: The three main river reaches (MRR) are tested by changing their length (L) and their roughness (K).

3.3. Results

Figure 5 shows the hydropeaking indicators (mean annual drawdown ranges for 10 minutes time step) for operated and natural catchments. For the latter, the mean daily variations between 1.14 and 1.26, coming mostly from precipitation and snow melt, are quite small.

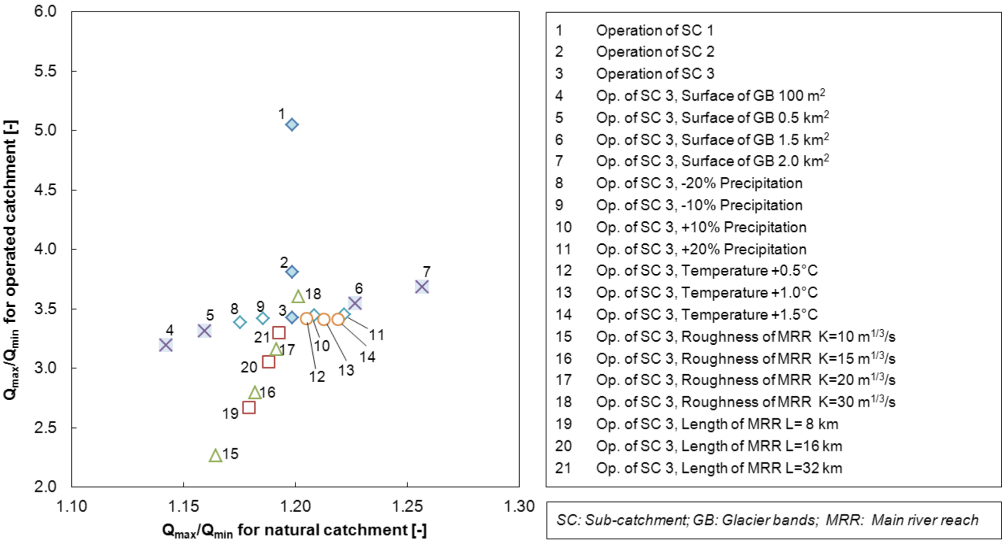

Figure 5 Comparison of hydropeaking indicators for natural and operated catchments at the catchment outlet for the year 2005

For the operated catchment, highest drawdown ranges are measured in winter, when the base discharge is low. Important hydropeaking occurs when the power house outlet is close to the catchment outlet. A factor of nearly 2 is achieved due to the routing effect of the river, which is optimal for long and rough reaches. The influence of morphology, a parameter acting on the flow downstream of the turbine, is measured especially for operated catchments with fluctuating flow regime. Meteorologic and hydrologic parameters influence the inflow of the reservoir as well as the residual flow. The turbine controls the outflow of the operated sub-catchment. When more water is available, turbining sequences are just longer, but do not have a major impact on drawdown range. Glaciers have the highest influence on the natural flow regime. A completely glaciated upper catchment (surface of GB 2.0 km^2) generates slightly higher flow variations because of the higher glacier melt during the daytime.

4. HYDROPEAKING IN THE UPPER AARE RIVER

Hydrologic processes depend on a large number of parameters and their modelling is complex. Therefore the hydrological-hydraulic model's accuracy has to be tested by a real case simulations. The gauging station of Brienzwiler at the outlet of the upper Aare River catchment is 13 km downstream of the turbine outlets of the Innertkirchen 1 (39 m^3/s) and Innertkirchen II (29 m^3/s) powerhouses. The statistical analysis of flow data shows, that due to turbining operations the average summer discharge decreased by 20% between 1925 and 2007, whereas winter discharge doubled. 80% of the days, hydropeaking indicators for the non-operated catchment between 1925 and 1928 were lower than 1.3 (Figure 6). This value has increased by turbining operations up to 4.4.

For testing the model's ability in reproducing highly fluctuating flow, the calibrated model was used for the simulation of the year 2005, chosen due to operation data availability. By applying in the model the power plant operations as done in 2005, slightly lower drawdown ranges are generated, e.g. 3.4 for the 80% fractile (Figure 6). The implemented kinematic wave theory does not give a better accuracy for heavily fluctuating flow. Despite of this limitation, the model allows simulating hydropeaking for different scenarios.

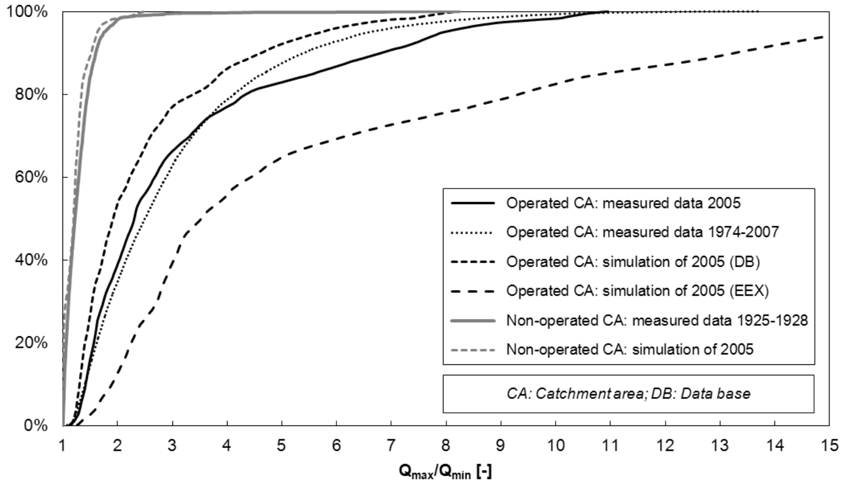

Figure 6 Probability of drawdown ranges for simulated and measured hydrographs at BAFU gauging station at Brienzwiler (outlet of upper Aare River catchment) for a 1 h time step

Assuming a production only driven by the spot market (EEX), drawdown ranges would increase (Figure 6). The reason for this difference is the Innertkirchen II power plant. Nowadays its production is mostly run-of-river, because of missing reservoir capacities. Spot market would induce short interruptions and as a result increase daily flow fluctuations. The simulation of 2005 without hydropower scheme shows slightly lower drawdown ranges than measured between 1925 and 1928. The influence of the kinematic wave model is less important because of the more constant flow. Therefore the parameter study shows that bigger glaciers as in 1925 generate higher flow variations because of higher melt during daytime. Another reason could be the structure of precipitation or temperature. Similar phenomenon occurred for the simulation of the year 2004.

5. CONCLUSION AND OUTLOOK

The parametric study reveals the influence of meteorologic, hydrologic and morphologic parameters on flow in an Alpine catchment area. It becomes more important when the turbining capacity is low or the operated catchment is small. Climate change (higher temperature and glacier melt) has only minor impact on hydropeaking and electricity market issues (higher volatility) will probably increase it. Therefore mitigation measures have to be foreseen. A restricted turbine operation mode may be theoretically an efficient measure from an environmental point of view but endangers the energetic and economic sustainability of the electricity production by high-head storage hydropower plants, having the task to provide peak energy during high demand periods and to regulate the electricity grid. As such, constructive mitigation measures have to focus on reducing hydropeaking downstream of the powerhouse outlets. The model will be able to compare and optimize constructive and operative mitigation measures and to deliver flow time series for ecological rating.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Baumann, P. and Klaus, I. (2003), *Gewässerökologische Auswirkungen des Schwallbetriebes - Ergebnisse einer Literaturstudie*, Bundesamt für Wald und Landschaft (BUWAL), Berne, Switzerland.

Baumann, P., Meile, T. and Fette, M. (2005), *Synthesebericht Schwall/Sunk, Publikation des Rhone-Thur Projektes*, EAWAG, WSL, LCH-EPFL, VAW-ETHZ, Switzerland.

Bieri, M., Schleiss, A.J. and Fankhauser, A. (2010), *Modelling and simulation of floods in alpine catchments equipped with complex hydropower schemes*, in A. Dittrich et al. (Eds) *River Flow; Proc. intern. symp.*, Braunschweig, September 8 – 10, 2010, pp. 1420-1428.

Favre, H. (1935), *Etude théorique et expérimentale des ondes de translation dans les canaux découverts*. Dunond, Paris.

García Hernández, J., Jordan, F., Dubois, J., Boillat and J.-L. and Schleiss, A. (2007), *Routing System II: Flow modelling in hydraulic systems*, Communication 32 du Laboratoire de Constructions Hydrauliques, Lausanne.

Halleraker, J.H., Saltveit, S. J., Harby, A., Arnekleiv, J.V., Fjeldstad, H.-P. and Kohler, B. (2003), *Factors influencing stranding of wild juvenile brown trout (salmo truita) during rapid and frequent flow decreases in an artificial stream*, River Research Applications 19, pp. 589-603.

Harby, A., Schauterleute, J., Sundt, H., Bakken, T., Clarke, K., Mader, H., Merigoux, S., Noack, M., Schmutz, St., Scruton, D. and Vehanen, T. (2010), *Environmental Impacts of Artificial Flow Fluctuations. Overview and Examples*, *8th International Symposium on Ecohydraulics (ISE 2010)*, *Proc. intern. symp.*, Seoul, September 12-16, 2010, pp. 778-779.

Pellaud, M. (2007), *Ecological response of a multi-purpose river development project using macro-invertebrates richness an fish habitat value*, PhD thesis N° 3807, EPFL, Lausanne.

Schaefli, B. (2005), *A conceptual glacio-hydrological model for high mountainous catchments*. Hydrology and earth system sciences 9(1-2), pp. 95-109.

Schneider, M., Kopecki, I. and Tuhtan, J. (2010), *Application of a Habitat Simulation Model for the Investigation of Hydropeaking Effects in an Alpine River*, *8th International Symposium on Ecohydraulics (ISE 2010)*, *Proc. intern. symp.*, Seoul, September 12-16, 2010, pp. 798-799.

Stranner, H. (1996), *Schwallwellen im Unterwasser von Spitzenkraftwerken und deren Reduktion durch flussbauliche Massnahmen*, Schriftenreihe zu Wasserwirtschaft, Technische Universität Graz, Graz.

VAW-LCH (2006), *Kraftwerksbedingter Schwall und Sunk, Eine Standortbestimmung*, VAW 4232, LCH 05-2006, Zürich and Lausanne.

Vibert, R. (1939), *Répurcrussions piscicoles du fonctionnement par éclusées des usines hydroélectriques*, Bulletin français de pisciculture 116, pp. 109-115.