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Modelling and simulation of floods in alpine catchments equipped with complex hydropower schemes

M. Bieri & A.J. Schleiss
Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions (LCH), Lausanne, Switzerland

A. Fankhauser
Kraftwerke Oberhasli AG (KWO), Innertkirchen, Switzerland

ABSTRACT: The simulation of run-off in an alpine catchment area equipped with complex hydropower schemes is presented by the help of an especially developed tool, called Routing System, which can combine hydrological modelling and operation of hydraulic elements. In the hydrological forecasting tool tri-dimensional rainfall, temperature and evapotranspiration distributions are taken into account for simulating the dominant hydrological processes, as glacier melt, snow pack constitution and melt, soil infiltration and run-off. The advantage of this object-oriented modelling tool is the integration of routing in rivers as well as hydraulic structures such as water intakes, reservoirs, turbines, gates and valves. The model allows simulating the operating mode of complex storage hydropower plants and its impacts on the downstream river system for different scenarios, taking into account natural and anthropogenic influences. The paper presents the modelling of the complex Oberhasli hydropower scheme, probably one of the most complex one in Switzerland. The development and calibration of the hydrological model is explained. First results are shown at the example of the flood event of 2005. The effect of the existing reservoirs and their management on flood routing is highlighted.

Keywords: Hydrological modelling, Run-off simulation, Alpine catchment areas, Storage hydropower plants, Flood routing, Multi reservoir operation

1 INTRODUCTION

In order to estimate the run-off in complex catchment areas, production and routing of flow are calculated by numerical models. Flood forecasting and management, optimisation of water use as well as sediment transport problems need a tool for run-off estimation. A large number of various prediction models exist. Their application domain is limited to specific conditions, like model scale, flow regime (flood or low flow) or datasets available. The quality of the results varies and depends on type and complexity of the model.

The semi-distributed conceptual code *Routing System* (Dubois 2005) is appropriate for hydrological forecast in high mountainous catchment areas. It is based on a concept developed by Schaefli (Schaefli 2005). Tri-dimensional rainfall, temperature and evapotranspiration distributions are used for simulating multiple hydrological processes. The model is able to produce 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.

In the framework of a research project on hydropeaking, a discharge prediction model was developed for the complex Oberhasli hydropower scheme in the upper Aare River basin upstream of Lake Brienz in Switzerland. It has been calibrated and validated during simulation. All hydroelectricity production data of the existing hydropower plants as well as the corresponding meteorological datasets were implemented.

The results are evaluated in terms of Nash coefficient, volume ratio and peak flow ratio. The initial configuration presents a good correlation with the observed data, confirming the robustness of the model. The model allows to correctly reproduce the hydrological cycles. The hydrographs of the 1987 and 2005 flood events were properly simulated.

The calibrated and verified model was then used to study the influence of the initial water level in the main reservoirs on the outflow of the catchment area for the flood of 2005. The contribution of the hydraulic scheme to flood routing was analyzed through simulations without the reservoirs and power plants.

2 THE UPPER AARE RIVER BASIN

At the end of the 19th century, the area of the Grimsel and Sustenpass was recognized as particularity appropriate for hydropower exploitation. Heavy rainfalls, large retention areas, solid granitic underground as well as important differences of altitudes by short horizontal distances provide an optimal conditions for a hydropower storage scheme (Schweizer et al. 2008). The first concrete dams were built between 1925 and 1932. Since then, a complex scheme with nine power plants and eight reservoirs has been constructed (Figures 1 and 2). The largest reservoirs are the lakes Oberaar (57 Mm^3), Grimsel (94 Mm^3), Gelmer (13 Mm^3) and Räterichsboden (25 Mm^3). In an upgrading program, the operator of the power plant, the *Kraftwerke Oberhasli AG* (KWO), foresees a large number of technical, economical and ecological improvements of the scheme, such as an increase of the electric power of the machines and storage capacity of the reservoirs.

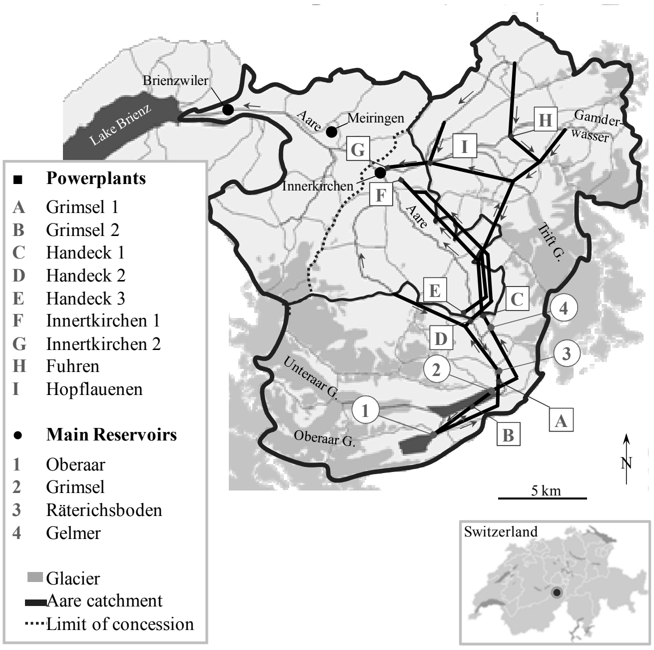

Figure 1. Catchment of the upper Aare River upstream Lake Brienz with the implemented Oberhasli hydropower scheme

The upper Aare River, also called Hasliaare, springs in the glaciers of Unteraar and Oberaar at the altitude of 2000 m a.s.l. and flows nowadays through several artificial reservoirs (Oberaar, Grimsel, Räterichsboden), in which the main part of the water is temporally accumulated to be turbined in the power plants of Grimsel, Handeck and Innertkirchen if required. In Innertkirchen the water is given back to the Aare River immediately downstream the confluence with Gadmerwasser, the river draining the eastern part of the catchment area. After the Aare Gorge the Aare River achieves the main valley of Meiringen and enters Lake Brienz at Brienzwiler.

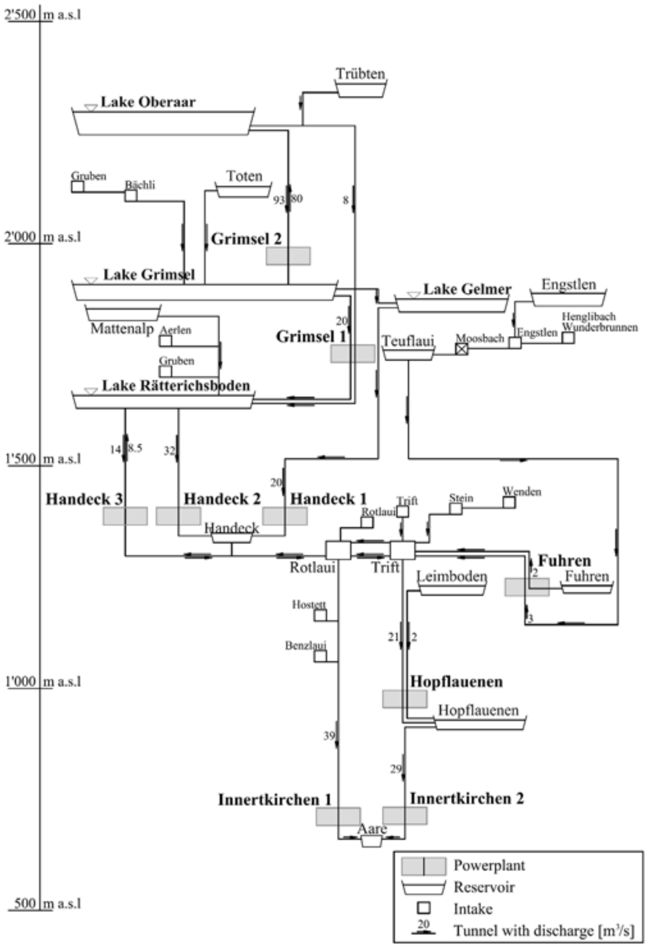

Figure 2. Oberhasli hydropower scheme

The surface of the upper Aare River basin is 554 km^2, where 21% was glaciated in 2003. The hydrologic regime of the river is therefore glacial. The average annual discharge is 35 m^3/s.

3 DATA SOURCES

For the simulations various input datasets are needed. The meteorological data are available from the 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 Hasliaare catchment (Figure 3).

The discharge, used to calibrate and validate the model, is measured every ten minutes on the Aare River in Brienzwiler in an installation operated by the Federal Office of Environment (BAFU). Figure 3 shows the location of the gauging station.

The KWO, an industrial partner and supporter of the research project, made accessible the hydraulic characteristics of the hydropower scheme, operation rules and historical data from the last 30 years of exploitation. Daily sums of turbined and pumped volumes as well as the water levels in the four main reservoirs were delivered as well as hourly averages for 2005. These datasets allowed calculating the inflow of the ten sub-catchments operated by KWO (Figure 6).

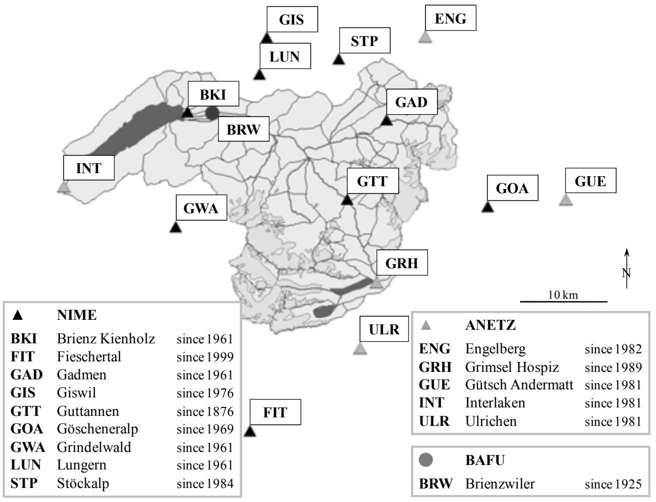

Figure 3. The upper Aare River catchment with official meteorological and hydrological gauging stations with date of beginning of measurements

4 MODEL DEVELOPMENT

4.1 *Modelling concept*

Routing System software is used for the semi-distributed conceptual modelling. It is based on object-oriented programming, describing the hydrological and hydraulic functions related to snow-melt, glacier melt, soil infiltration, surface run-off and flood routing. The description of the network is carried out with the help of six hydraulic functions – generation of flow, flow transport, storage, diversion, confluence and flow regulation – which can be related to each other. The 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 gravity centre 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 (García Hernández et al. 2007): glacier, snow, infiltration (GR3) and surface run-off (SWMM). Depending on the presence of glaciers, two types of sub-basins are aggregated. In alpine regions, evapotranspiration (ETP) can be neglected.

The glacier sub-basin (Figure 4) 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 in 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 Q_{tot} of the glacier sub-basin.

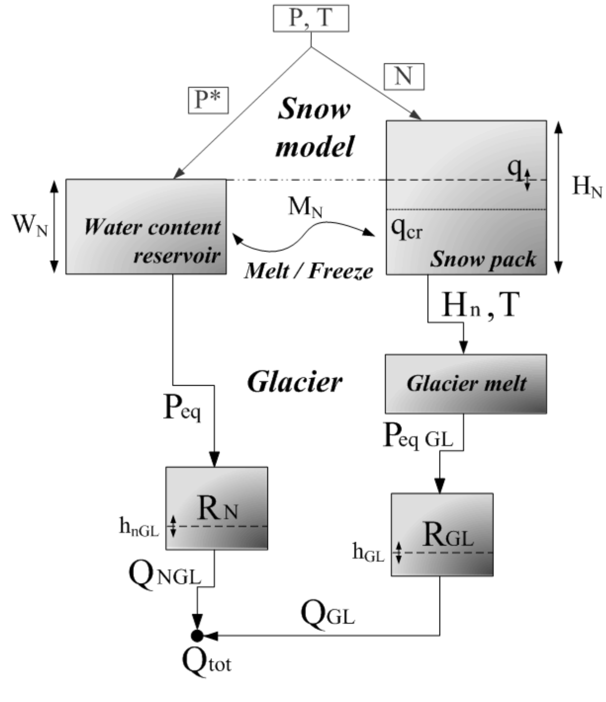

Figure 4. Modelling of glacier sub-basin

In the non-glacier sub-basin (Figure 5), 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 (Consuegra et al. 1998). 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 (Metcalf 1971) 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.

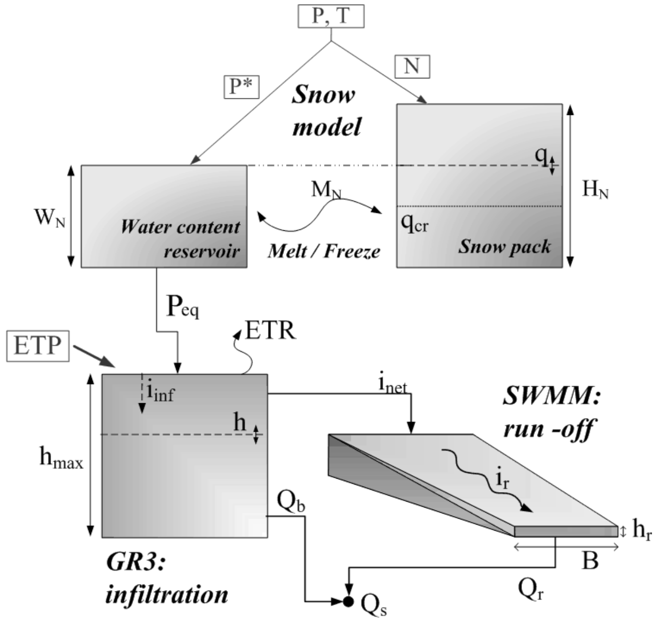

Figure 5. Modelling of non-glacier sub-basin

4.2 *Calibration and validation*

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 basic hydrological formulas as well as the calibration process are explained in detail in García Hernández et al. (2007).

For each band, precipitation and temperature are interpolated from the 14 meteorological stations, if situated in the influence zone of 30 km. 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 infiltration reservoir k are then calibrated. Finally the Strickler coefficient $K_{s,}$ mainly influencing the flood events in time, is defined.

The model was then pre-calibrated over ten 15 months' periods for a one hour time step continuous simulation by using meteorological, hydrological and exploitation datasets. The hydrological parameters of the ten sub-catchments operated by KWO (Figure 6) were optimised independently. The natural Hasliaare catchment was calibrated by data from the gauging station of BAFU. The results 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.

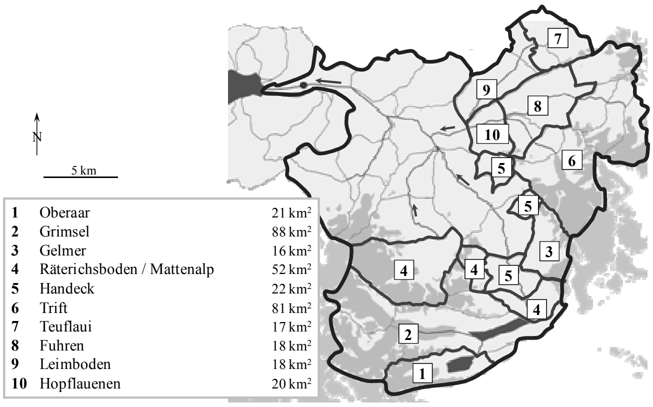

Figure 6. Sub-catchments operated by KWO

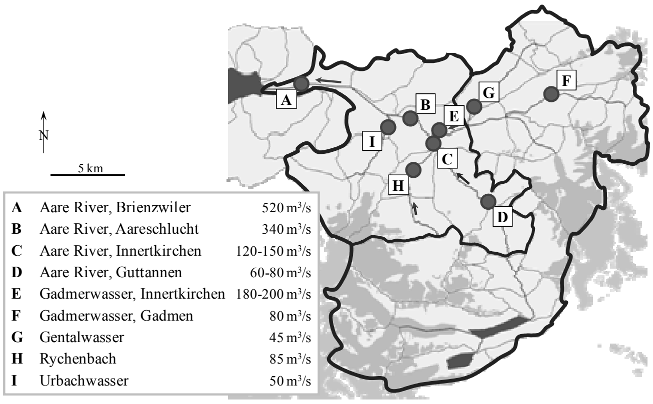

Figure 7. Observed (reconstructed) peak flow in the Hasliaare catchment for the 2005 flood event

In a second step, the model was calibrated by the extreme flood event of August 2005 and validated by the flood of August 1987. The peak flow of the Aare River in 2005 of 444 m^3/s (called measured discharge) was the highest value ever measured in Brienzwiler, corresponding statistically to a return period of about 100 years (Figure 8). The valley between Meiringen and Lake Brienz was largely inundated and, therefore, the whole discharge could not be measured at the gauging station. A post-analysis of the event allowed an estimation of the real peak and a reconstruction of the hydrograph (called observed discharge). Flooding was not simulated by *Routing System*. For this reason the model was calibrated using this adapted hydrograph with a peak of 520 m^3/s. Further peak flow estimations in the uninfluenced catchments (Figure 7) were used for comparison. The 1987 flood event produced only insignificant inundation. Without any adaptations of coefficients, the measured and simulated outflow in Brienzwiler could have been compared (Figure 9).

The simulations started at the beginning of the hydrological year in order to obtain parameters independent from the initial conditions. The results were compared to the inflow from the subcatchments, to the observed outflow in Brienzwiler and to the peak flow estimations in terms of Nash coefficient (1), water volume ratio r$_{\text{vol}}$ (2) and peak flow ratio r$_{\text{peak}}$ (3):

$$\text{Nash} = 1 - \frac{\sum_{t=0}^{n} (Q_{obs}(t) - Q_{sim}(t))^2}{\sum_{t=0}^{n} (Q_{obs}(t) - \overline{Q_{obs}})^2} \tag{1}$$

$$\text{r}_{\text{vol}} = \frac{V_{sim}}{V_{obs}} = \frac{\sum_{t=0}^{n} Q_{sim}(t)}{\sum_{t=0}^{n} Q_{obs}(t)} \tag{2}$$

$$\text{r}_{\text{peak}} = \frac{Q_{sim\ \max}}{Q_{obs\ \max}} \tag{3}$$

where $Q_{obs}(t)$ = observed discharge, $Q_{sim}(t)$ = simulated discharge, Q_{obs} = mean observed discharge, V_{sim} = simulated volume, V_{obs} = observed volume, $Q_{sim\ \max}$ = peak simulated discharge and $Q_{obs\ \max}$ = peak observed discharge.

Table 1. Evaluation of calibration (2005) and validation (1987) at Brienzwiler

	Calibration (2005)	Validation (1987)
Nash coefficient	0.98	0.90
Volume ratio r$_{\text{vol}}$	1.03	1.05
Peak flow ratio r$_{\text{peak}}$	0.99	1.00

The objectives of a Nash coefficient higher than 0.8, a volume ratio r$_{\text{vol}}$ between 0.9 and 1.1 and a peak flow ratio r$_{\text{peak}}$ between 0.9 and 1.1 were achieved (Table 1). The simulated hydrograph for 2005 (Figure 8) shows the main characteristics as the reconstructed one. Only the double-peak could not be reproduced.

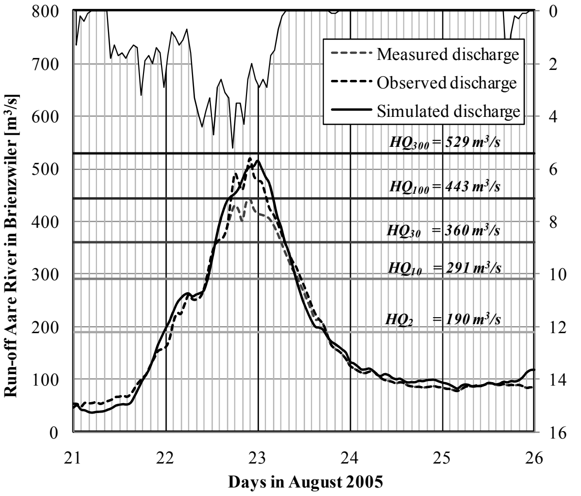

Figure 8. Calibration of the model with 2005 flood event

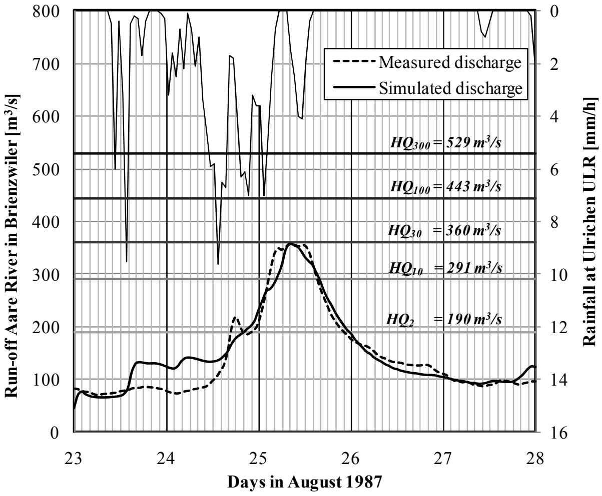

Figure 9. Verification of the model with 1987 flood event

During calibration and verification of the model, rainfall patterns of all available meteorological stations were compared to generated discharges. As for the Hasliaare catchment the most relevant Grimsel station was not operational in 1987, the rainfall of Ulrichen is plotted (Figure 9). Both flood events show coherence between rainfall and discharge. Even if the simulated flood of 1987 generates too high values at the beginning.

Table 2. Comparison of observed (reconstructed) and simulated peak flow for 2005 flood event [m^3/s]

	River Reach	$Q_{obs\ \max}$	$Q_{sim\ \max}$	r$_{\text{peak}}$
A	Aare River, Brienzwiler	520	515	0.99
B	Aare River, Aareschlucht	340	358	1.05
C	Aare River, Innertkirchen	145	147	1.01
D	Aare River, Guttannen	60	46	0.77
E	Gadmerwasser, Innertkirchen	180	173	0.96
F	Gadmerwasser, Gadmen	80	79	0.99
G	Gentalwasser	45	46	1.02
H	Rychenbach	85	81	0.95
I	Urbachwasser	50	52	1.04

Table 2 shows the comparison of observed respectively reconstructed ($Q_{obs\,\max}$) and simulated ($Q_{sim\,\max}$) peak flow at nine different locations in the downstream Hasliaare catchment for the 2005 flood event. Beside the upper Aare River in Guttannen, which is influenced by a high number of water intakes on rivers, peak flow ratios r_{peak} fall all in the confidence interval between 0.9 and 1.1 and confirm the plausibility of the model in the non-operated part.

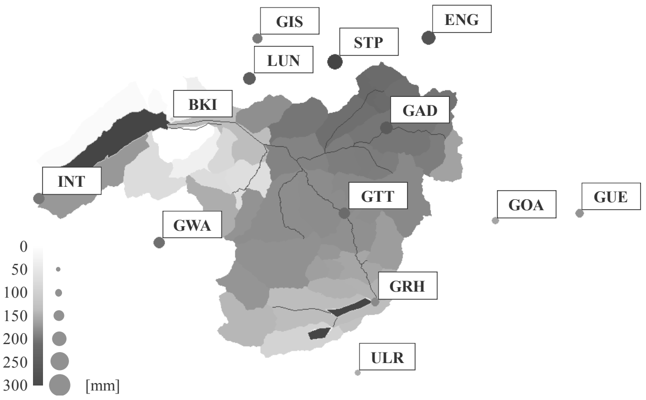

Figure 10. Cumulated rainfall during 2005 flood event (between 21st and 26th of August 2005) with gauging stations

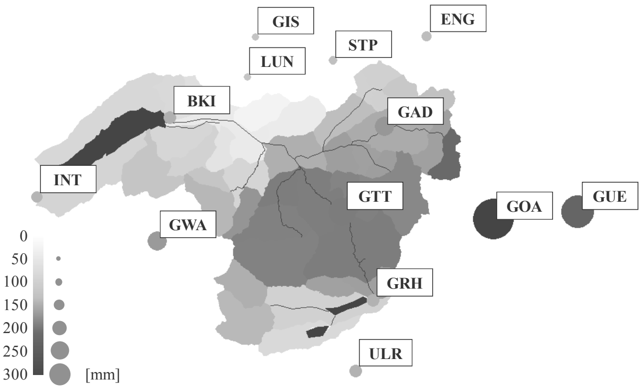

Figure 11. Cumulated rainfall during 1987 flood event (between 23rd and 28th of August 1987) with gauging stations

The model has thus been successfully calibrated and can be used for simulations of other scenarios as well as for flood forecasting. A particularity of the two simulated floods is namely the quite different distribution of rainfall. During the flood event of 2005 (Figure 10), maximum rainfall was measured in the north-eastern part of the river basin. For the event of 1987, the gravity centre of the precipitations is in the east (Figure 11). An interesting analysis could consist in a scenario with other rainfall distributions, for example in the south, where the large reservoirs are situated. Simulations

Due to operational constraints the Grimsel and the downstream located Räterichsboden (Räbo) reservoirs had exceptionally low water levels on 21st of August 2005. Their flood retention volume was therefore much higher than normally. To evaluate the retention effect of the large reservoirs of the Oberhasli scheme, three scenarios of filling degrees were defined, simulated and compared (Table 3).

Table 3. Initial water levels [m a.s.l.] and filling degree for scenarios I to III on 21st of August 2005 (00:00)

	Oberaar	Grimsel	Gelmer	Räbo
I	2’297.7 (85%)	1’882.1 (35%)	1’848.1 (92%)	1’749.3 (57%)
II	2’295.7 (80%)	1’904.7 (88%)	1’847.9 (91%)	1’756.2 (72%)
III	2’303.0 (100%)	1’908.8 (100%)	1’849.7 (100%)	1’767.0 (100%)

- *Scenario I* corresponds to the situation as happened in 2005. The calibration discussed in chapter 4 confirms the reliability of the model.
- *Scenario II* presents average levels in August, calculated over the last 10 years. This case corresponds to the most likely situation with filling degrees between 70 and 90%.
- *Scenario III* is a worst case scenario assuming full reservoirs at 21st of August 2005. This quite hypothetic case is the upper limit of the sensitivity analysis.
- *Scenario IV* evaluates the influence of the whole hydropower scheme. By removing all reservoirs and power plants, the unequipped catchment was analysed.

The meteorological input data was the same for all simulations. The turbining and pumping operation was considered on the basis of an analysis of statistical data. When a reservoir is full, the emergency scenarios as defined in the operation rules are applied. Taking into account the downstream conditions, they foresee maximum turbine operation when the water level exceeds a limit near to the crest level the spillways. To avoid oscillating behaviours between on and off, the emergency turbining is stopped when the level achieves a preliminarily defined lower limit. Between the Grimsel and Räterichsboden reservoirs, power plant Grimsel 1 is used in scenarios II and III for emergency turbining. This power plant has a maximum capacity of 20 m^3/s and was out of service during the 2005 flood event, which was the reason for the low reservoir levels.

5 RESULTS AND DISCUSSION

5.1 *Results*

The simulated curves have similar characteristics (Figure 12). All of them provide a local maximum in the morning of 22nd of August and the peak at midnight the same day. Scenarios I and II results in the same hydrograph. The higher discharge of scenario III is caused by emergency turbining due to full reservoirs. The missing retention volume after the main precipitations induces also higher flows in the Aare River in the following days. The same effect is detected in scenario IV, which corresponds to a hypothetic case of a non-equipped, natural catchment area.

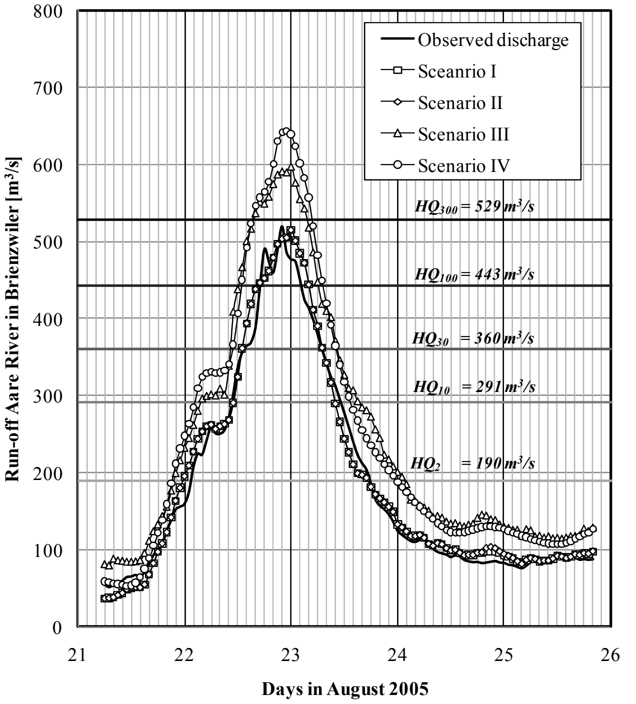

Figure 12. Hydrographs of the 2005 flood event for scenarios I to IV (scenarios I and II are superposed)

Table 4. Observed (Ref.) and simulated volumes of hydrographs between 21st of August (12:00) and 24th of August 2005 (12:00) [Mio m^3]

		Scenario			
	Ref.	I	II	III	IV
Aare River, Brienzwiler	63.2	64.5	64.5	78.9	81.6
Aare River, Innertkirchen		14.3	14.3	24.2	32.9
Aare River, Guttannen		4.0	4.0	13.8	18.8
Gadmerwasser, Innertkirchen		18.4	18.4	18.4	27.4
Gadmerwasser, Gadmen		8.8	8.8	8.8	11.2

Table 5. Observed (Ref.) and simulated peak flows for 2005 flood event [m^3/s]

		Scenario			
	Ref.	I	II	III	IV
Aare River, Brienzwiler	520	515	515	588	642
Aare River, Innertkirchen	145	147	147	189	269
Aare River, Guttannen	60	46	46	95	143
Gadmerwasser, Innertkirchen	180	173	173	173	214
Gadmerwasser, Gadmen	80	79	79	79	89

The analysis of peak flow (Figure 12 and Table 5) reveals much higher return periods for the simulated floods than those defined by the measured values. This fact points out the difficulty of statistical flood characterisation in a highly affected catchment area, like the one of the Hasliaare River.

5.2 *Influence of initial reservoir water level*

Compared to the flood event of 2005, scenarios I and II do not result in higher flood discharges (Tables 4 and 5). Looking at the example of Grimsel reservoir (Figure 13), it can be seen, that the average water level as initial condition for scenario II does not lead to the complete filling of the reservoir. Therefore neither spillway release nor emergency turbining are taking place and the power plant is managed as usual. The difference between increasing and decreasing level gradients of scenarios I and II can be explained by the V-shaped geometry of the reservoir.

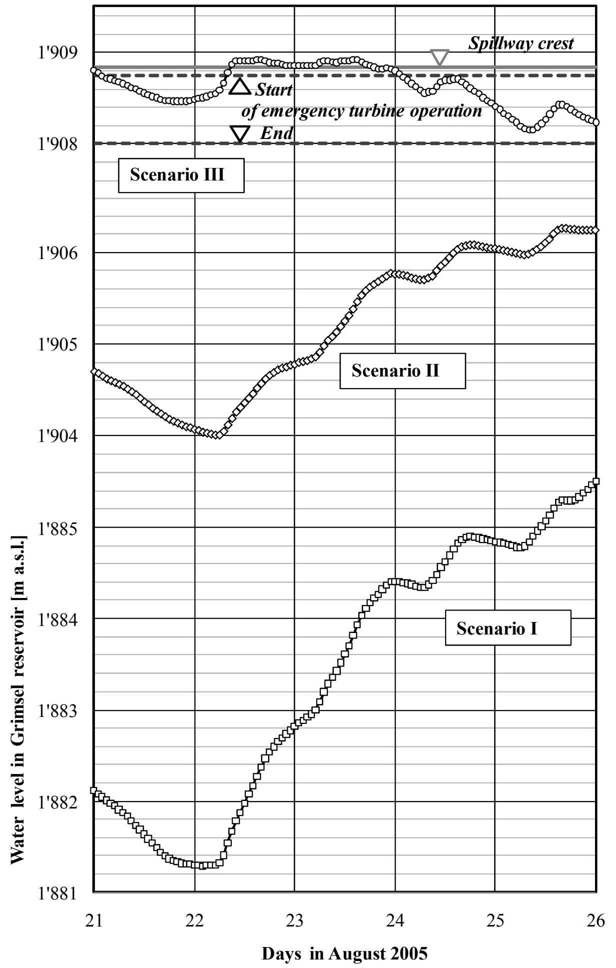

Figure 13. Level variations in the Grimsel reservoir for scenarios I to III as defined in Table 3

Assuming full reservoirs at the beginning of the flood, as in scenario III, an initial decrease of level occurs due to water transfer to Gelmer reservoir (Figure 13). With increasing inflow, emergency turbine operation by Grimsel 1 as well as flood evacuation by the spillways starts. The latter operate during 30 hours. The lower limit of emergency turbine operation is not achieved before 26th of August.

The adapted initial reservoir conditions of scenario III influence only the flow regime of the downstream reaches of the Aare River. The hydrographs of Gadmerwasser remain unchanged (Tables 4 and 5).

The simulations reveal as expected the importance of the initial water level in the reservoirs for flood retention. Sufficient retention volume allows a considerable flood routing. If the initial water level is important, peak flow can only be reduced by an intelligent management of the plant, like shown for scenario III.

5.3 *Influence of the hydropower complex in the catchment area*

Due to the hydropower complex, the peak flow of the 2005 flood event could have been reduced by 127 m^3/s, from 642 m^3/s to 515 m^3/s, which means 20%. Comparing scenario IV without hydropower plants to the worst case scenario III with the full reservoirs at the beginning of the flood, an increase of peak flow not only in the Aare River valley but also in the catchment area of Gadmerwasser can be observed (Table 5). Because of the missing water intakes in the rivers and small reservoirs, the peak flow of Gadmerwasser in Innertkirchen increases by about 25%. Furthermore a new increase in the Aare River reaches upstream of the confluence is simulated. Therefore not only the presence of retention volume is important but also an appropriate management of the power plants and reservoirs. This is even more crucial when the maximum rainfall does not occur in the catchments controlled by the reservoirs (Figure 10).

6 CONCLUSION

The built simulation model is robust and generates satisfying results for observed flood events. The simulated hydrographs are very similar to the measured respectively observed ones. Additional discharge data could increase the performance. The dominant operated discharge of the hydropower scheme helps to calibrate the model. The conformity between hydrological and hydraulic elements in the system is shown. This is even more relevant by taking into account the complexity of the scheme.

The *Routing System* software is accurate for simulating alpine catchments. It allows analysing different scenarios by taking into account the influence of a hydropower scheme. Boundary and initial conditions as well as input data can be adapted and their effects evaluated.

For the 2005 flood event, the peak flow without reservoirs is reduced by about 20%. The retention effect of reservoirs of the Oberhasli hydropower scheme is approved. Therefore storage hydropower plants can take an important role in flood routing.

The hydrological-hydraulic model can also be used for real time decision making, as well as for the evaluation of ecohydraulic issues.

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