INFLUENCE OF CLIMATE CHANGE ON FUTURE OPERATION OF A COMPLEX STORAGE HYDROPOWER SCHEME IN THE SWISS ALPS

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ABSTRACT

For the case study area of the upper Aare River catchment in Switzerland with large mountain glaciers, where a complex storage hydropower scheme is located, the impact of climate change on runoff was simulated. Future runoff was assessed for the ongoing century using the semi-distributed conceptual hydrological modeling approach *Routing System*. Glacier mass balance and runoff were computed in hourly time steps for precipitation and temperature distributions. The model was calibrated using ice volume changes and daily runoff at five gauging stations in the catchment area. The scenarios for future climatic conditions up to 2099 were developed from historical temperature and precipitation data series. The herein presented C2SM-ETHZ scenario, neglecting any global greenhouse gas reduction in future, predicts an almost complete de-glacierization of the upper Aare River basin until the end of the century. Runoff from glacier melt will initially slightly increase, followed by a decrease due to important ice mass losses. Total runoff will decrease by 2% until 2050 and by 18% until 2099. Significant decrease of runoff related to glacier melt must be considered for future hydropower management.

INTRODUCTION

More than 40% of European hydroelectric power is produced in Alpine countries (Schleiss 2002). High-head storage hydropower plants (HPP) contribute significantly to peak energy production as well as grid regulation. Switzerland supplies about 20% of the total Alpine hydroelectric production. Reservoirs at high altitude store rainfall as well as snow and glacier melt during summer in order to cover energy demand in winter. The melt water runoff from the glaciers is needed for the filling of the reservoirs. These specific water resources might diminish or even run dry in partly ice-covered watersheds. An assessment of the impact of climate change and glacier retreat on runoff by hydrological modeling is needed for a sustainable use of hydropower in future.

Alpine catchments are highly sensitive to climate change due to glacier shrinkage (UNEP 2007). Every year 2 to 3% of the glacier volume in the European Alps is disappearing (Haeberli et al. 2007). Estimations predict a reduction of the ice-covered areas by 75% already during the coming decades (OcCC 2007). A change in the hydrological regime of the Alpine rivers is therefore expected (Huss 2011). As the glaciers are readjusting to the rising temperature, higher discharges occur during the summer for a limited number of years depending on glacier size, hypsography and catchment characteristics until the

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glaciers either find a new equilibrium state or completely disappear. Runoff will then decrease, whereas peak flow would be shifted from summer to early summer or spring (Braun et al. 2000). The annual runoff hydrograph changes from ice melt dominated (glacial) to snowmelt dominated (nival) (Horton et al. 2006). In these regions, the changing hydrological regime will cause a high impact on irrigation, water supply, flood management as well as hydropower production.

Routing System applies a semi-distributed conceptual approach and allows interconnecting hydrological and hydraulic elements. Thus, this tool is currently applied in the field of flood as well as hydropower management in the Alps (Bieri and Schleiss, 2012). The reservoir-based precipitation-runoff transformation model is based on the GSM-SOCONT (Glacier Snow Melt SOil CONTribution) approach in order to simulate runoff using hourly or daily temperature and precipitation data as input. To extend its applicability to climate change issues, the glacier simulation tool has been extended to dynamic glacier volume evolution for long-term runoff simulation. Inflow hydrographs for an Alpine catchment area containing a complex hydropower scheme are presented for the on-going century, taking into two scenarios. Challenges for water resources management are highlighted.

CASE STUDY

The study site is the upper Aare River catchment upstream Lake Brienz in Switzerland (Figure 1). The surface area of the upper Aare River basin, located between 564 m a.s.l. (Lake Brienz) and 4274 m a.s.l. (Finsteraarhorn), is of 554 km^2. Six main glaciers as well as several ice patches lie within the study area. At the end of the 19th century, hydropower development started. The first dams were built by the Kraftwerke Oberhasli AG (KWO) hydropower company between 1925 and 1932. Since then, a complex scheme with nine powerhouses and several reservoirs has been developed. The largest reservoirs are Lake Grimsel, Oberaar, Räterichsboden and Gelmer, fed by several intakes collecting water in side valleys.

Simulations for the whole upper Aare River catchment have been performed. For this study, only the results of the hydropower relevant upper part are presented. Lake Oberaar at 2303 m a.s.l. is the highest reservoir in the scheme and is fed by melt water from the Oberaar Glacier, which has shrunk by 1.6 km since 1930. The also east-exposed Unteraar Glacier above Lake Grimsel has two main tributaries and is with its 13 km length the fourth largest glacier in the Swiss Alps. In the western part of the catchment area, Gauli Glacier is located in the Urbach valley upstream of the Mattenalp intake. Due to substantial retreat in recent years, two main lakes appeared in the glacier forefield. A lake was also formed in the eastern drainage basin downstream of the fastly shrinking Trift and Stein Glaciers. These glaciers as well as the Steilimi Glacier are steep, north-exposed mountain glaciers, located in the overall catchment of the Trift intake.

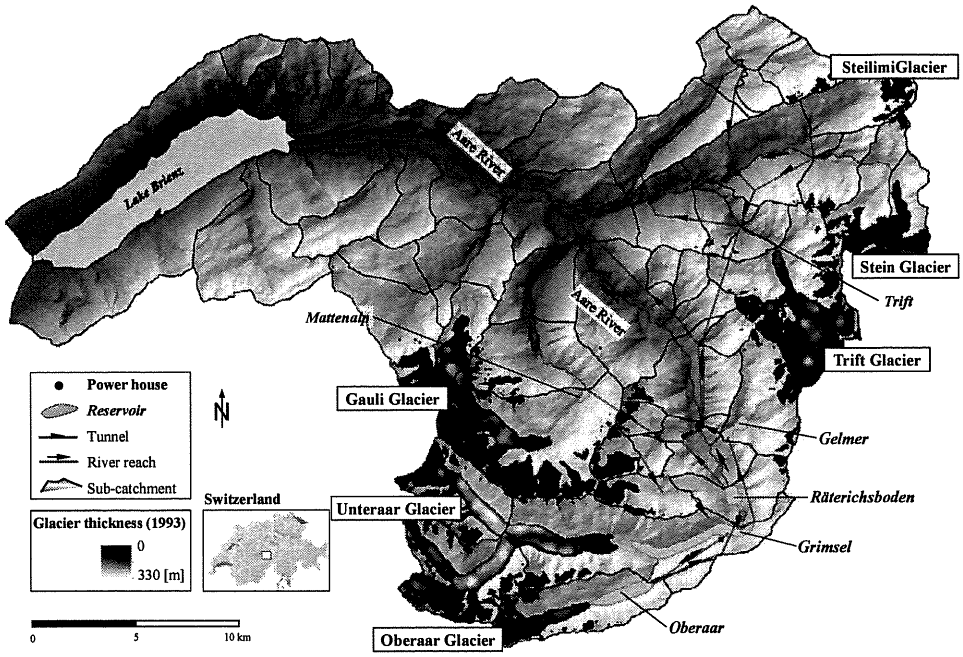

Figure 1. Location and overview map of the upper Aare River catchment with the Oberhasli hydropower scheme (KWO) and the glacier extensions in 1993 with hydropower relevant sub-catchments main reservoirs and intakes.

For the model set-up several, data series were available for this study, as climate data, discharge measurements, digital elevation model (DEM) and topographic maps for glacier surface area and thickness. Homogenized time series of temperature and precipitation from 1980 to 2010 for a large number of gauging stations are provided by the Federal Office of Meteorology and Climatology (MeteoSwiss). Fourteen of them are located in and close (< 20 km) to the upper Aare River catchment and are therefore taken into account for the model calibration. For the spatial distribution of the meteorological variables the method of Shepard is applied. Precipitation and temperature for a given elevation band are obtained by weighting the data of the input weather stations.

KWO made accessible historical exploitation data. Daily sums of turbine and pump volumes as well as water levels are available, allowing calculation of the inflow to the four main reservoirs Oberaar, Grimsel, Gelmer and Räterichsboden (including Mattenalp intake) as well as to the Trift intake.

The spatial discretization of the catchment area is carried out based on a DEM with a grid size of 25 m (Swisstopo). GIS-based analysis of topographic maps allows defining the ice thickness and surface changes between 1980 and 1993 and therefore the average annual ice thickness change over this period. To estimate the initial ice volume, the glacier bed topography is computed using the inverse ice flow law together with a shallow ice approximation (Haeberli und Hoelzle 1995, Linsbauer et al. 2009) as discussed in Terrier et al. (2011).

MODELING AND SIMULATION

The initial stage of the upper Aare River catchment was established for October 1980 (Figure 2a). The modeling approach has two levels of discretization for each defined sub-catchment. The first distinguishes between ice-covered and non ice-covered parts. The second level divides the sub-catchment into elevation bands with a homogenous hydrological behavior (Figure 2b), containing a non ice-covered part defined by its surface area S_{ngl}, and if present the surface area S_{gl} and thickness of glacier. The five main ice-covered drainage basins are divided into elevation bands of 150 m. In the model, all discharges and volumes are given in water equivalent (e.w.).

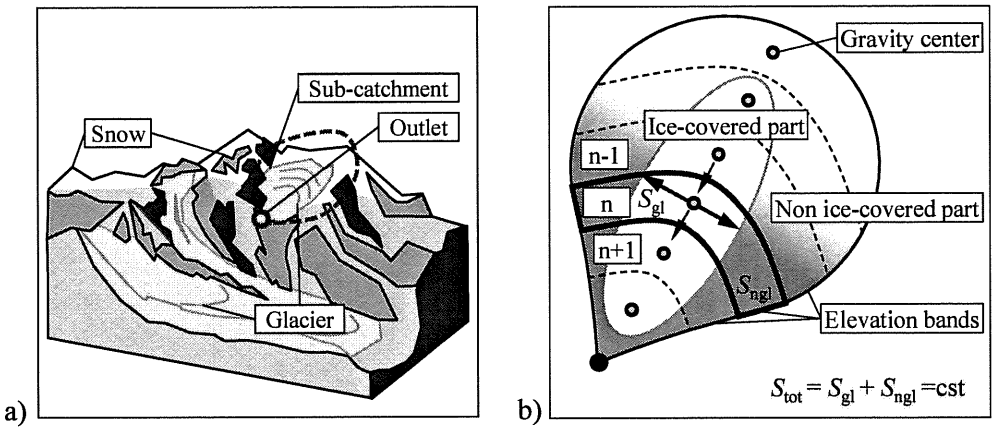

Figure 2. Model discretization: (a) Sketch of a high-mountainous catchment area containing glacier and snow; (b) partly ice-covered sub-catchment area with subdivision in elevation bands.

Routing System undertakes hydrological modeling by the reservoir-based precipitation-runoff transformation model GSM-SOCONT (Schaefli et al. 2005). The semi-distributed conceptual numerical approach takes into account spatial precipitation and temperature distributions for simulating the dominant hydrological processes: In the non ice-covered part of the elevation band, three modules – snow, infiltration and runoff – are used. The ice-covered part of the elevation band is composed of two elements, namely snow and glacier. The hydrological processes are described in Bieri and Schleiss (2012). The purpose of the glacier model is to simulate the glacier mass balance and the discharge at its outlet over a long period (Bieri 2012). In a semi-distributed conceptual model with the applied discretization, glacier evolution in terms of surface area and height changes in time cannot be precisely simulated, but its general dynamics as well as the runoff are well described. In *Routing System*, the total discharge from the ice-covered part of the elevation band depends on the storage processes in the two linear reservoirs for snow and ice. The surface area changes linearly influence the soil infiltration model GR3 as well as the surface runoff model SWMM. The glacier surface area is therefore updated every time step, which is 1 h in this study.

The model has several parameters to be calibrated. Some of them are kept constant for the whole Aare River catchment. The calibration is achieved for each of the five catchments individually. Maximum data availability is required for long-term runoff estimations from glacierized catchment areas. *Routing System* undertakes a stepwise procedure focusing on parameter groups. They are calibrated using available daily runoff measurements at the outlet of each catchment (1980-2008), detailed glacier volume changes for Oberaar and Unteraar Glaciers (1980-1993) and mean annual ice thickness changes from topographic maps (1980-1993). The results are compared to the observed inflow in terms of the Nash and Sutcliffe efficiency criterion NSE in addition to water volume ratio r_{vol}. The calibration over the time period from 1981 to 1993 shows good agreement between measured and simulated runoff (NSE: 0.66-0.88; r_{vol}: 0.85-1.09).

Two different climate scenarios are herein presented. The reference climate scenario (0°C) just reproduces the climate of the past 30 years over the next 100 years (Figure 3). The C2SM-ETHZ scenario is built using the developments of the Centre for Climate Systems Modeling (C2SM) of the Swiss Federal Institute of Technology Zurich (ETHZ), neglecting any carbon-emission mitigation (A1B). The implemented Delta Change Method gives the difference between the reference climate period 1980-2009 and two future climate periods (Bosshard et al. 2011). For every weather station in Switzerland values have to be applied to the reference temperature and precipitation for 2021-2050 and 2070-2099. Between these periods, a linear interpolation of the delta changes is applied.

The C2SM-ETHZ scenario shows an overall increase of temperature of about +4°C by 2099. The increase of temperature compared to the reference climate period is always positive (Figure 3). The intra-annual variability gives high increase for both future climate periods especially in summer, whereas in spring moderate increase is forecasted. Precipitation has no relevant deviation until 2099. Its main change for the C2SM-ETHZ scenario is intra-annual. For 2021-2050 precipitation will slightly decrease in spring and summer, whereas a high peak up to +30% is shown in October and November.

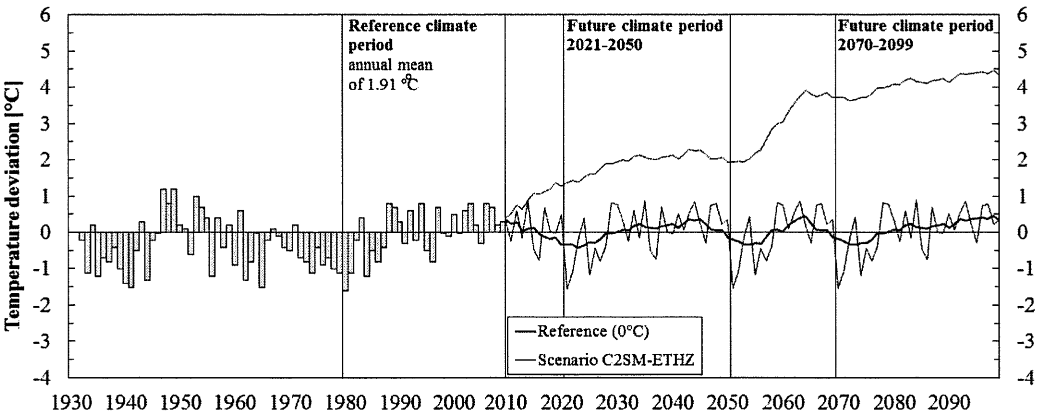

Figure 3. Deviation of the historic and forecasted temperature from the 1980-2009 reference climate period for the weather station Grimsel Hospiz (Tendency curves of average over 11 values; same annual inter-annual fluctuations as scenario 0°C).

As glacier extension and densely space and time distributed climate data was only available for 30 years, calibration period may seem short compared to the simulation time of 90 years. But the important glacier shrinkage during the last three decades justifies the applied data ranges. Long term climate changes have been taken into account for the development of the applied scenarios (Bosshard et al. 2011).

After re-simulation of the period between 1981 and 2009, a simulation with hourly time step is run for each of the five scenarios from 2010 to 2099. Temperature, precipitation, snowfall, snowmelt, ice melt, glacier volume, evaporation, infiltration as well as runoff are updated hourly. Data analysis of all elements in the catchment areas is done with daily mean values for the total simulation period. The simulation has been repeated for other climate scenarios and sensitivity analysis has been performed. In this article, only the results of the reference climate (0°C) and the C2SM-ETHZ scenarios are presented.

RESULTS

Analyzing the behavior of the Gauli Glacier (Figure 4), its mass balance shows that in the past nearly all elevation bands were losing volume, the lower the greater. It would continue in the same way, when applying the C2SM-ETHZ scenario with high temperature increase and therefore a considerable ice volume loss at the beginning of the simulation period. The glacier between 2100 and 2400 m a.s.l. disappears between 2020 and 2030, the highest elevation bands in the mid-century. The reference climate scenario illustrates this phenomenon even better by continuous de-glaciation of the lower bands, with the upper bands remaining stable.

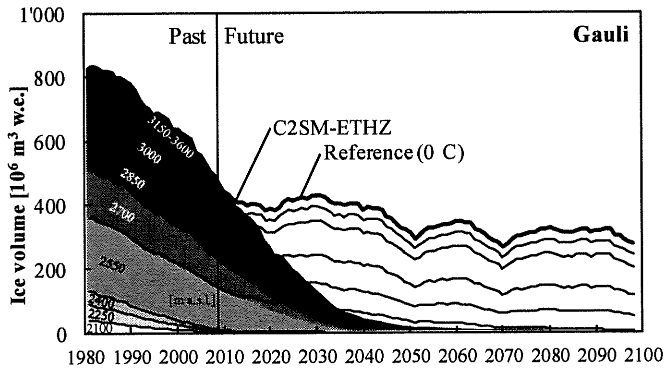

Figure 4. Ice volume evolution for the elevation bands of the Gauli Glacier for the reference climate (0°C) and the C2SM-ETHZ scenarios.

The future specific annual runoff of the catchment area of Grimsel, containing the Unteraar Glacier, shows similar behavior as for the glacier melt (Figure 5). The C2SM-ETHZ scenario reveals an increasing discharge until 2025, followed by a mainly decreasing period until the end of the century. Glacierization decreases for the reference climate (0°C) as well as the C2SM-ETHZ scenario. Disregarding the reference climate scenario with some stabilization of size after the loss of the lower glacier bands towards the second half of the simulation period, the glacier is not able to reach a steady state as the increase of temperature is too fast. The glacier completely disappears until 2099 for the C2SM-ETHZ scenario. Thus, glacier melt is expected to increase for the first 10 to 15 years. Due to considerable glacier mass losses, water from ice melt decreases for the following years.

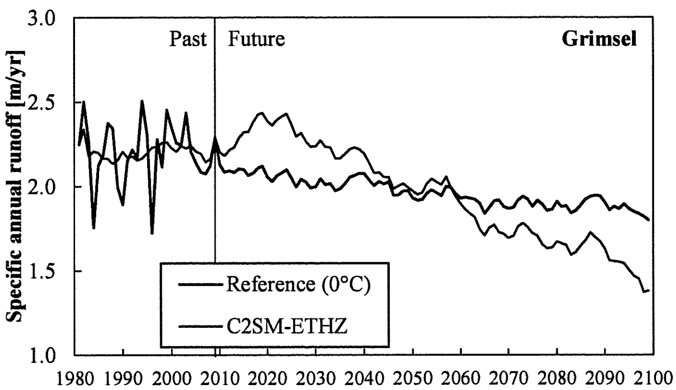

Figure 5. Specific annual runoff of the Grimsel catchment for the reference climate period (past), the reference climate (0°C) and the C2SM-ETHZ scenarios (Tendency curves of average over 11 values for future runoff normalized by the catchment surface area of S = 89.6 km^2).

Intra-annual runoff distribution is shown by the mean annual hydrographs for the catchment areas of Grimsel and Räterichsboden/Mattenalp (Figure 6). The daily runoff is plotted as the average value over the past (1980-2009) and the two future climate periods (2021-2050 and 2070-2099) for the two investigated scenarios. The reference climate scenario (0°C) has a similar runoff behavior to the past (Figure 6/1). Peak flow remains the same. The reduction of the glacier mass influences the contribution of glacier melt. Thus, lower summer discharges are expected. The C2SM-ETHZ scenario (Figure 6/2) transforms today's hydrograph from glacier melt- to snowmelt-dominated. The complete loss of ice mass, the high temperatures, more rainfall in spring and less precipitation in summer lead to an increase of the runoff peak in spring, which is on average 2% for Grimsel and 24% for Räterichsboden/Mattenalp for 2021-2050 and 10% and 34% respectively, for 2070-2099. Because of the fast melt of the glaciers and the ice mass losses, summer runoff decreases. Higher temperatures and precipitation in October and November increases winter runoff.

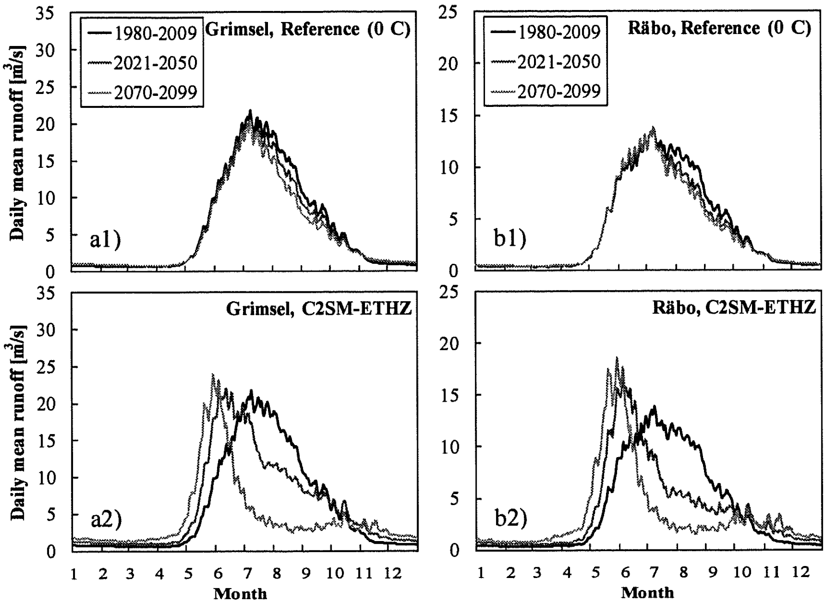

Figure 6. Average annual hydrograph of the catchment areas of (a) Grimsel and (b) Räterichsboden/Mattenalp (Räbo) over the past (1980-2009) and the two future climate periods (2021-2050 and 2070-2099) for (1) the reference climate (0°C) and (2) the C2SM-ETHZ scenarios.

Table 1 summarizes the average annual values of water balance components for the simulated scenarios over the five hydropower relevant catchment areas. As mentioned above, mean precipitation remains constant. Warming leads to an increase of evaporation and glacier melt. The latter decreases in future decades due to glacier disappearance. In any case, runoff does not only decrease but reveals a new intra-annual redistribution.

Table 1. Area-weighted specific annual precipitation P [m/yr], evapotranspiration RET [m/yr], ice melt $Q_{icemelt}$ [m/yr] and total runoff Q_{out} [m/yr] as well as relative runoff in July and August $Q_{out\,7\text{-}8}/Q_{out}$ [%] for the five catchment areas (S_{tot} = 261.0 km^2) for the reference climate (0°C) and the C2SM-ETHZ scenarios.

		1980	2009	2021-2050		2070-2099	
		real	0°C	0°C	C2SM-ETHZ	0°C	C2SM-ETHZ
P	[m/yr]	41	2.44	2.48	2.48	2.44	2.44
RET	[m/yr]		0.14	0.15	0.23	0.16	0.32
$Q_{icemelt}$	[m/yr]		0.28	0.08	0.29	0.04	0.01
Q_{out}	[m/yr]		2.59	2.41	2.54	2.31	2.13
$Q_{out\,7\text{-}8}/Q_{out}$	[%]		46	44	29	43	14

CONCLUSION

The chosen modeling approach is an efficient and coherent way to analyze the impact of climate change on future runoff in Alpine catchment areas. *Routing System* is an approved model for hydrological-hydraulic simulations. A simple dynamic glacier tool was implemented. First applications have been realized for case studies in the Swiss Alps (Terrier et al. 2011). The semi-distributed model allows short simulation time. The division in elevation bands of 150 m does not take into account local effects of varying glacier thickness or exposition.

For the period from 2010 to 2099, time series of daily resolution are calculated by hourly updating of the meteorological, glaciological and hydrological parameters for climate scenarios for the upper Aare River catchment. For the C2SM-ETHZ scenario without carbon-emission mitigation, containing an increase of temperature of about 4°C by 2099, high glacier melt is predicted for the 21st century. An almost complete de-glacierization of the upper Aare River basin for the period between 2050 and 2099 will take place. Runoff from glacier melt will initially slightly increase, followed by a decrease due to ice mass losses. Total annual runoff will decrease by 2% until 2050 and by 18% by the end of the 21st century. Higher temperature increases evaporation and accelerates snowmelt. Reduction of glacier melt in summer and earlier and faster snowmelt in spring change the runoff regime from glacio-nival to nival. For Alpine catchment areas, significant decrease of runoff related to glacier shrinkage combined with new peak flow in spring must be considered for future hydropower, irrigation but also for flood risk management.

The goal of the present study was the development of a simple but reliable approach to estimate future runoff from glacierized catchment areas. The novel formulation and modeling method allows definition of the effects of climate change on the behavior of Alpine glaciers for different scenarios. The resulting hydrographs, highly important for future HPP operation, could be simulated. The model is well adapted for runoff estimations in Alpine catchments, especially when containing hydropower plants. Reliable estimation and optimization of future energy production and therefore economic efficiency can be done for existing as well as new hydropower facilities.

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