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Climate change effects on snow melt and discharge of a partly glacierized watershed in Central Switzerland (SoilTrec Critical Zone Observatory)

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ABSTRACT

A comprehensive hydrological modeling study in the drainage area of a hydropower reservoir in central Switzerland is presented. Two models were tested to reproduce the measured discharge dynamics: (1) a detailed energy-balance model (ALPINE3D) primarily designed for snow simulations; (2) a conceptual runoff model system (PREVAH), including a distributed temperature-index snow and ice melt model. Considerable effort was put into distributing available meteorological station data to the model grids as forcing data. The recent EU regional climate modeling initiative ENSEMBLES provided up-to-date climate predictions for two 30-a periods in mid and late 21st century. These were used to estimate evolutions in the water supply of the hydropower reservoir in response to expected climate changes. The simulations suggest a shift of spring peak-flow by almost two months for the end of the century. Warmer winter temperatures will cause higher winter base-flow. Due to glacier retreat, late-summer flow will decrease at the end of the century.

1. Introduction

In the Alps, streamflow and water resource availability critically depend on snow and glacier melt. While the capabilities of numerical models have made significant progress in recent years, it remains challenging to accurately quantify the hydrological response of mountain watersheds to climate warming. Apart from uncertainties related to atmospheric forcing data for predictive model runs, dealing with snow and glacier melt, steep terrain, complex micro climatic effects, and unknown groundwater processes poses substantial difficulties to numerically reproduce the hydrological behavior of alpine watersheds.

Here a comprehensive hydrological study is presented for the drainage area of a hydropower reservoir in central Switzerland (lake Goescheneralpsee in canton Uri; Fig. 1). The catchment is partly glacierized (20%) and spans over 95 km^2 of alpine topography covering elevations between 1800 and 3600 m asl. This catchment is of particular interest as it encompasses the Damma glacier forefield site, which is a Critical Zone Observatory (CZO) of the SoilTrec project (Soil Transformations in European Catchments).

As is often the case, long-term hydrometeorological data is largely unavailable for the area, apart from reservoir water level measurements. Various measuring devices were installed at the beginning of this study in 2007 and provided valuable evaluation data for both meteorological input and model results. The infrastructure includes three automatic meteorological stations, continuous discharge measurements at three sites, and two remote camera systems for snow-covered area.

Discharge measurements in the feeding streams display strong diurnal and seasonal fluctuations due to snowmelt in spring and glacier melt later in summer. Two models were tested to reproduce the measured discharge dynamics: (1) a detailed energy-balance model (ALPINE3D) primarily designed for snow simulations; (2) a conceptual runoff model system (PREVAH), including a distributed temperature-index ice-melt model. Considerable effort was put into distributing available meteorological station data to the model grids as forcing data. Also, as both models do not simulate glacier flow, attention was given to regularly update glacial areas based on externally provided glacier extent scenarios.

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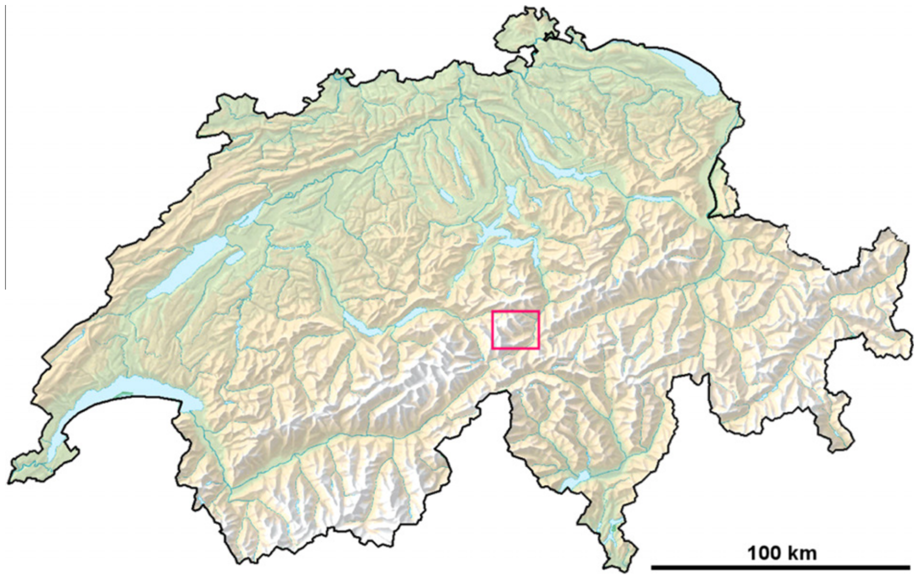

Fig. 1. Location of the study catchment in Switzerland.

The recent EU regional climate modeling initiative ENSEMBLES provided up-to-date climate predictions for two 30-a periods in mid and late 21st century. These were used to estimate evolution in the water supply of the hydropower reservoir in response to expected climate changes. The simulations suggest a shift of spring peak-flow by almost two months for the end of the century. Warmer winter temperatures will cause higher winter base-flow. Due to glacier retreat, late-summer flow will decrease at the end of the century.

2. Models

2.1. Energy-balance model

ALPINE3D is a spatially distributed model for predicting and analyzing snow-dominated surface processes in mountainous terrain (Lehning et al., 2006). It is based on the one-dimensional snowpack model SNOWPACK (Bartelt and Lehning, 2002) and includes relevant energy-balance terms for snow and ice development as well as shading and scattering of radiation. Six meteorological parameters are required as hourly input to this model: air temperature, relative humidity, wind speed, precipitation, incoming long-wave radiation and incoming short-wave radiation.

2.2. Conceptual runoff model

PREVAH is a semi-distributed hydrological modeling system particularly enhanced for applications in mountain regions (Viviroli et al., 2009). The process-oriented model uses the concept of hydrological response units and requires as input the same meteorological variables as ALPINE3D. Incoming long-wave radiation can also be computed by the model by providing hourly or daily records of sunshine duration.

3. Preparation of the input dataset

3.1. Meteorological data

In a previous study, Magnusson et al. (2011) evaluated the correlation of local short-term meteorological measurements against data originating from several nearby long-term weather stations. In this study, the two locations showing best correlation and providing records long enough for the 1981–2010 reference period were selected.

Alpine meteorology is highly affected by altitudinal gradients. Attention was thus given to appropriately interpolate raw meteorological data. All interpolation methods were based on the findings of Magnusson et al. (2011) who carried out similar simulations for the Damma glacier subcatchment.

Among all parameters, the spatial distribution of snowfall had a particular impact on modeling results. An interpolation algorithm accounting for terrain curvature and slope provided the best results, which were assessed against snow-covered area data from automatic cameras. An altitudinal gradient of 5% per 100 m was also applied to solid precipitation.

Ten climate change scenarios for temperature and precipitation were used to create the 2021–2050 and 2070–2099 meteorological datasets. Incoming long-wave radiation was recalculated based on predicted air temperature. Relative humidity, wind speed and incoming short-wave radiation were left unchanged.

3.2. Future glacier extent

As the catchment feeding Goescheneralpsee is approximately 20% glacierized, an appropriate estimation of future glacier extent is important for hydrological simulations. ALPINE3D can model ice formation from snow but does not have a module allowing for glacier flow. Glacier extent was, therefore re-adjusted every 5 years based on externally provided scenarios. Glacier thickness was uniformly set to 50 m. To avoid effects on runoff formation of this unphysical ice distribution, a spin-off period of one year preceded each 5-a modeling step.

4. Results and discussion

The model performance was first evaluated for the well-instrumented Damma glacier catchment, which represents approximately 10% of the total area feeding the hydroelectric reservoir. This subcatchment encompasses the Damma glacier forefield which is an intensively studied CZO. Both models reproduced the typical runoff patterns of a highly glacierized catchment well: strong diurnal and seasonal dynamics due to snow and gla-

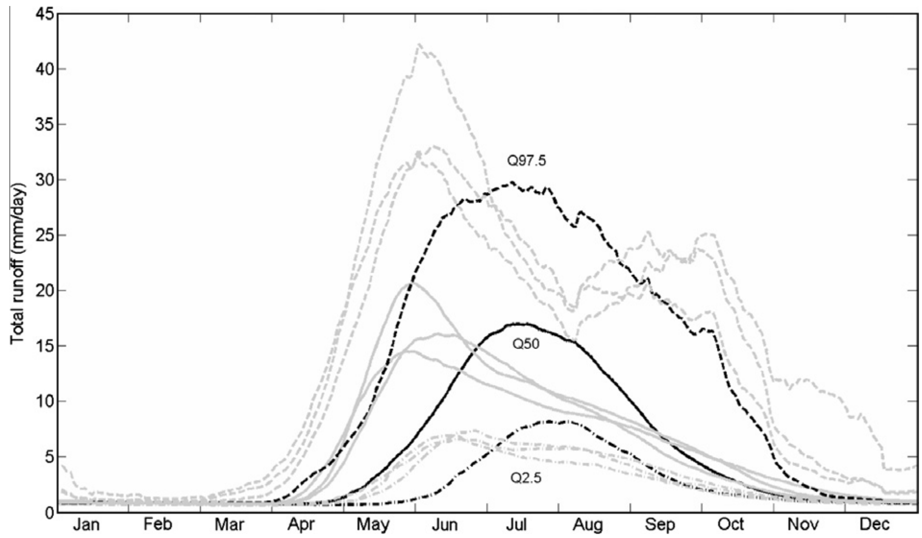

Fig. 2. ALPINE3D results (2.5%, 50% and 97.5% quantiles) for the reference 1981–2010 period (black) and three 2070–2099 climate change scenarios (gray).

cier melt variations. Good results were achieved thanks to the specific effort put into interpolating input parameters. The energy-balance model showed slightly high melt rates on the glacier in summer. This is presumably due to the meteorological stations providing the input data being snow-free early in the season. A bilinear temperature correction parameterization (Shea and Moore, 2010) was introduced over snow-covered areas to account for glacier micro-meteorology. On the other hand, the conceptual model had difficulties in early spring, when melt water is still retained in the snowpack.

Three 30-a periods were then modeled at the scale of the bigger catchment (95 km^2): 1981–2010 as the reference period, 2021–2050 and 2070–2099 as climate change simulations. Model performance was evaluated against 13 years of runoff data, which were provided by the reservoir operator. The results showed a good fit for both models with correlation and Nash–Sutcliffe coefficients superior to 0.85.

Differences in predictions among climate change scenarios (10 different combinations of Global Circulation Models and Regional Circulation Models were tested) were smaller than the overall shift with today's observations. Climate change simulations thus agree qualitatively well and spread over a range distinctively apart from today's observations. Both models provided similar results for median runoff as well as extreme percentile values (Q2.5% and Q97.5%). Future median and extreme values were within a range similar to today's values. Yearly runoff volumes showed an increase by approximately 20% during 2020–2050 before falling under today's value towards the end of the century. The main transformations between past runoff and climate change simulations are both significantly earlier spring melt and the diminution of late-summer flow due to glacier retreat. Fig. 2 presents ALPINE3D results for the reference period and three 2070–2099 climate change scenarios.

5. Conclusions

The initial aim of this study was to provide the operator of the hydropower reservoir with future inflow predictions. As part of this project, detailed work was also carried out on the hydrology of the Damma Glacier CZO. Although discharge shows significant variations among years, on average, the reservoir inflow currently peaks in early July. The simulations suggest a shift of this peak by 2–4 weeks for mid century and by almost 2 months by the end of the century. The total annual discharge will increase in the near future with additional glacier melt. However, towards the end of the century, total discharge will start decreasing as some glaciers disappear.

Although the present study concentrates on surface hydrology, results of ALPINE3D simulations may be used (preferably at a higher resolution) to determine local snowmelt and thus groundwater recharge patterns. In the future, these could be linked to conceptual groundwater models specific to the Damma Glacier CZO and used as input to soil development models. Ongoing research is carried out to relate runoff data to groundwater level fluctuations at the Damma glacier forefield, both on daily and seasonal time scales. Also, the ability of ALPINE3D to accurately model soil moisture and groundwater flow, although currently limited, is the object of a recently started PhD project.

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