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Future runoff from a partly glacierized watershed in Central Switzerland: A two-model approach

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ABSTRACT

We present a comprehensive hydrological modeling study in the drainage area of a hydropower reservoir in central Switzerland. To investigate the response of this 95 km^2 alpine watershed to a changing climate, we used both a conceptual and a physically based hydrological model approach. The multi-model approach enabled detailed insights into the uncertainties associated with model projections of future runoff based on climate scenarios. Both hydrological models consistently predicted changes of the seasonal runoff dynamics, including the timing of snowmelt and peak-flow in summer as well as the future spread between high and low flow years. However the models disagreed regarding the evolution of glacier melt rates thus leading to a considerable difference in predicted annual runoff figures. The findings suggest that snow-glacier feedbacks require particular attention when predicting future runoff from glacio-nival watersheds.

1. Introduction

The importance of modeling climate change impacts on runoff in snow-dominated or glacierized regions has been highlighted in numerous studies (e.g. [24,2,14]). Changes in timing and amount of runoff from mountain watersheds will certainly impact the local ecology and water resources management which are relevant to the supply of drinking water, hydropower production and agricultural irrigation.

Uncertainties in climate change predictions arise from various steps in the modeling chain: emission scenarios which depend on economical and political decisions, global climate models (GCMs), regional climate models (RCMs) and finally the downscaling to the local weather station scale. Ensemble techniques are typically used to quantitatively assess the uncertainty of climatological models when climate change predictions are used as input to hydrological modeling (e.g. [9,13]). However this approach neglects any uncertainty associated with the hydrological model. Hydrological models are subject to inherent uncertainties, especially in high alpine terrain due to the ruggedness of the terrain and the high spatial variability of hydrological and atmospheric processes.

Most climate change hydrological studies have focused on results from conceptual models (e.g. [9,13,40]), mainly because such models have reduced meteorological data requirements and can be easily calibrated due to computational efficiency. Conceptual models are often highly parameterized and usually yield very good results for the climatologies and catchments they have been calibrated against. One can however question the adequacy of such models in a changing climate, as land use and meteorological forcing may dramatically evolve [12,22]. In this study we therefore employ both, a conceptual and a physically based model approach, to investigate the hydrological response of an alpine watershed to a changing climate. Concretely, we used (1) the detailed energy-balance model ALPINE3D, primarily designed for snow hydrological simulations [20], and (2) the conceptual runoff modeling system PREVAH [34], which includes a distributed temperature-index ice-melt scheme. We show common features and dissimilarities between the model results, both for a past reference period and for climate change simulations. Such a model comparison has been done for past data [11] but seldom, to this extent, on future predictions [8].

Physically-based distributed models such as ALPINE3D are typically more sensitive to limited or poorly interpolated meteorological data than conceptual models [8]. Being able to accurately

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provide distributed input data for a number of variables is therefore prerequisite for a successful model application. Considerable effort has been put into setting up and validating a meteorological input data methodology for the study area. In a preceding article, [23] evaluated the performance of ALPINE3D for the Dammareuss catchment which represents approximately 10% of the study area. Their effort towards an optimized regional setup of ALPINE3D constitutes an important foundation for this study.

2. Study site, data and models

2.1. The catchments

The drainage area feeds a 75 million m^3 hydropower reservoir in central Switzerland (lake Göscheneralpsee, N46°64.5′ E08°49.0′ in canton Uri, c.f. Fig. 1). The catchment is partly glacierized (20%) and spans over 95 km^2 of steep alpine topography covering elevations between 1792 and 3630 m a.s.l.

High-resolution land use data [33] were aggregated to three types: glacier, rock and alpine meadows. The vegetated area (28%) mainly consisted of alpine grass vegetation with minor shares of alpine dwarf scrubs (rhododendrons) and bushes (alders and willows). The reservoir is fed by a 42 km^2 natural catchment (yellow catchment in Fig. 1) and by two tunnels redirecting runoff from two neighboring valleys (green and purple catchments). This hydropower catchment encompasses the Dammareuss catchment (hatched area in Fig 1), which is a Critical Zone Observatory (CZO) of the BigLink and SoilTrec projects [6]. It constitutes a 10 km^2 sub-catchment that is 50% glacierized. The Dammareuss catchment was used to regionally validate the performance of ALPINE3D [23], before extending the simulations to larger scales in time and space, as described in this paper.

The discharge regime in the feeding streams is nivo-glacial, displaying strong diurnal and seasonal fluctuations due to snowmelt in spring and glacier melt later in summer. We do not expect karstic hydrological flow paths as the geology of the whole catchment is granitic [6].

Table 1 provides a summary of the main characteristics of both the hydropower catchment and the Dammareuss sub-catchment.

2.2. Hydrological models

2.2.1. ALPINE3D

ALPINE3D is a spatially distributed model for predicting and analyzing surface processes (energy and moisture fluxes, snowpack buildup and melt) in mountainous terrain [20,3,18]. It is based on the one-dimensional snowpack model SNOWPACK [19] and includes relevant energy-balance terms for snow and ice development as well as the shading of radiation by relief. 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. ALPINE3D was run at 200 m spatial resolution and on an hourly time step.

ALPINE3D's output consists of hourly volumes of glacier melt, snowmelt and rainfall. These values are available per pixel or as a catchment total. Surface runoff and infiltration processes are typically modeled outside of ALPINE3D, although an early version of PREVAH's runoff module can be run within ALPINE3D [20]. Here, we applied a simple linear storages runoff module as a post-processing step to the raw output from ALPINE3D. This module consists of four linear reservoirs: baseflow, quick sub-surface flow, glacier melt and a combined reservoir for snowmelt and for liquid precipitation on snow-free terrain. The runoff module was calibrated using inflow data for Göschernalpsee available between 1997 and 2010 (c.f. Table 1).

2.2.2. PREVAH

PREVAH is a semi-distributed conceptual hydrological modeling system particularly enhanced for applications in mountain regions

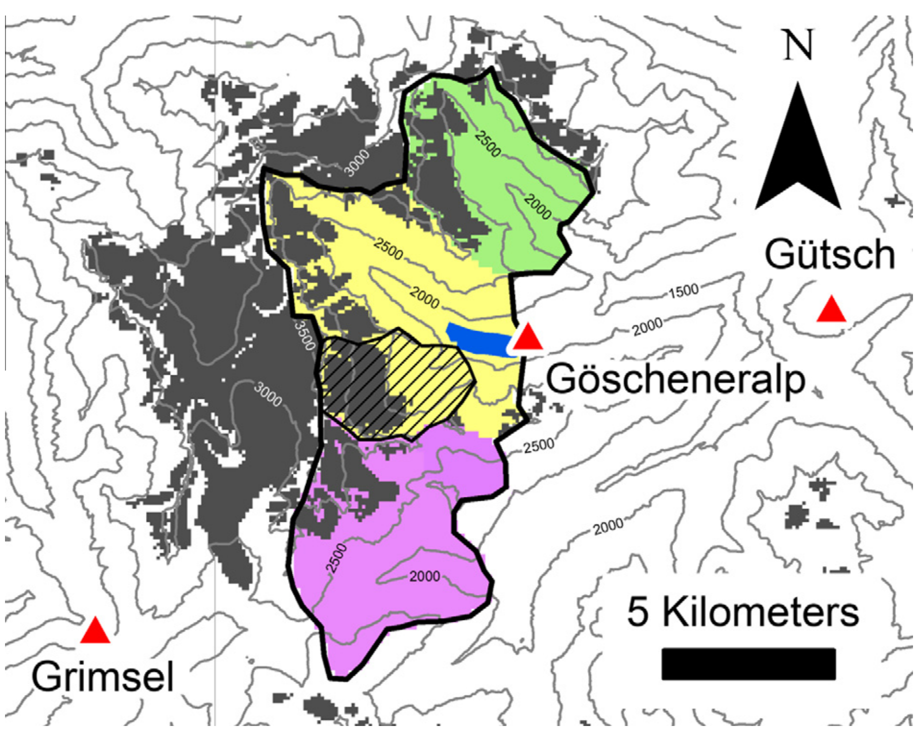

Fig. 1. Map of the study area. The catchment is delineated by the thick black line. The natural tributary to the reservoir Göscheralpsee is in yellow. In purple and green are neighbouring valleys, which are connected to the reservoir via tunnels. The Dammareuss sub-catchment is hatched in black. Relief is indicated by 500m contour lines and the glacierized area is denoted by dark gray shading (based on data for 2006–2010 from [28]). Red triangles mark the locations of long-term automatic weather stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)