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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

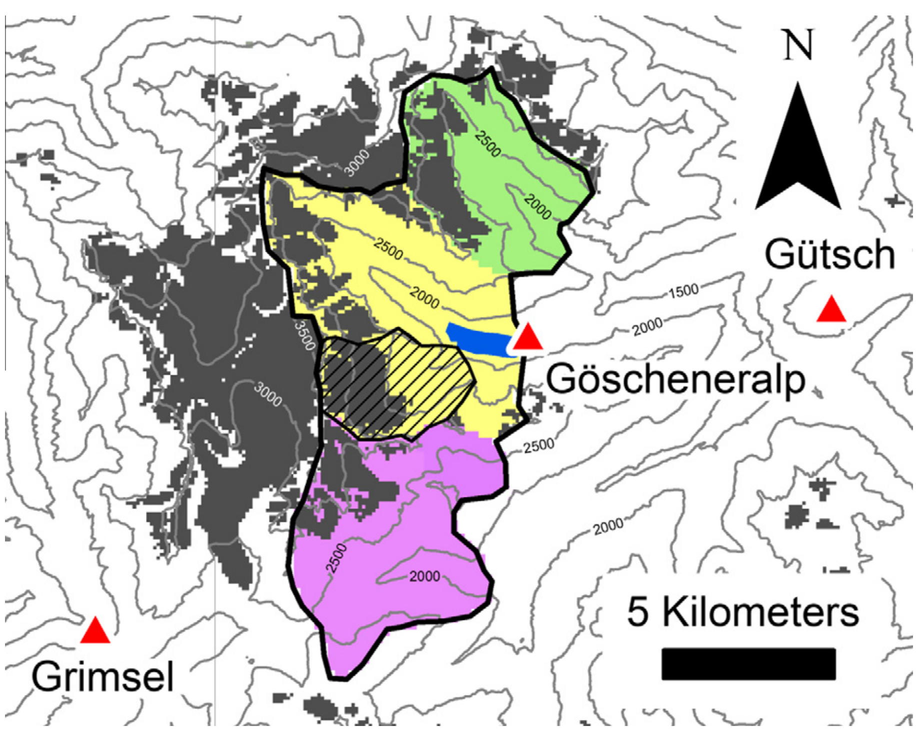

Fig. 1. Map of the study area. The catchment is delineated by the thick black line. The natural tributary to the reservoir Göscheralpsee is in yellow. In purple and green are neighbouring valleys, which are connected to the reservoir via tunnels. The Dammareuss sub-catchment is hatched in black. Relief 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.)

Table 1
Summary of the catchment properties. Note that average precipitation is an interpolated value whereas average runoff is measured.

Catchment	Area (km^2)	Altitude range (m a.s.l.)	Glacierized area (%)	Runoff records	Average yearly precipitation (mm/year)	Average yearly runoff (mm/year)
Göscheneralpsee	95	1792–3630	20	1997–2010	2000	2125
Dammareuss subcatchment	10	1940–3630	50	2007–2010	2400	2840

[34]. The model requires six meteorological variables as input: air temperature, relative humidity, wind speed, precipitation, incoming short-wave radiation and sunshine duration. The temporal resolution can vary between hourly and daily. For this study, the model was run with a 200 m resolution grid and on a daily time step.

PREVAH has extensively been used in studies devoted to water resources estimation [38,16] and operational hydrology throughout the Swiss Alps [1,39]. For this purpose, a substantial effort has been put into its calibration at a regional level based on many decades of hydrometerological data. In this study, as only 12 years of inflow data were available, each grid cell was attributed a set of well-calibrated parameters resulting from the calibration of several mesoscale basins. This is based on the calibration procedures described in [35,36], which delivered robust sets of regionalized parameters for any location in Switzerland. Limited additional calibration was needed for the present application in the Göscheneralpsee catchment. This concerned only the de-biasing of both liquid and solid precipitation (see Section "3.2.1 Water balance adjustment" in [34]).

The runoff generation module of PREVAH follows the general structure of the HBV model [11]. Its design consists of two linear reservoirs (upper reservoir for the unsaturated zone and lower reservoir for the saturated zone) connected by a percolation term. In the upper reservoir, surface runoff is generated upon passing a calibrated threshold content, while interflow is generated as long as the reservoir has some content. The lower reservoir yields the base flow component [11].

2.2.3. Key differences between both models

The main difference between the two models lies in the treatment of snow and glacier melt. ALPINE3D uses a full energy-balance approach, whereas PREVAH uses a degree day approach. For snowmelt and glacier melt, the Extended Melt Approach was used (see EMA in [37]). The temperature melt factor is seasonally variable for snow and firn to account for the variation in global radiation over the year. It is however constant for ice. The radiation melt factor is seasonally constant but differs between snow, firn and ice. This type of the degree-day approach is often used (e.g. [37,23,9]) to take into account the strong effect of net radiation balance on glacier melt.

Another difference in glacier melt is that once winter snow has melted away, PREVAH assumes an infinite depth of firn and ice, respectively, in the accumulation and ablation areas of the glacier. With ALPINE3D, as described in Section 2.4.2, the depth of ice is limited. For consequences of these model differences, refer to Section 4.3.

2.3. Meteorological input data

2.3.1. ALPINE3D

Climate change studies require long-term meteorological records. It has also been recognized that energy-balance models have particularly high requirements regarding meteorological forcing data. In a preceding study, [23] evaluated the correlation of local short-term meteorological measurements (all parameters in Table 2) against data observed at several nearby long-term automatic weather stations (ANETZ). In this case, we selected the 2 locations showing best correlation and providing records long enough for the 1981–2010 reference period. These stations are located at Gütsch (2283 m a.s.l.) and Grimsel (1977 m a.s.l.). An additional station (Göscheneralp, 1740 m a.s.l.), situated close to the centre of the catchment, provided daily precipitation records which were used to scale the hourly records from Gütsch to values more representative of the catchment. All ANETZ data were provided by MeteoSwiss (Fig. 1).

Alpine meteorology is highly affected by altitudinal gradients. Attention was thus given to appropriately interpolate meteorological station data. We based all interpolation methods on the findings of [23] who carried out non-prognostic hydrological simulations for the Dammareuss sub-catchment. Among all parameter interpolations, the spatial distribution scheme for snowfall had a particular impact on modeling results. An interpolation algorithm accounting for terrain curvature and slope [14] provided the best results, which were assessed against snow covered area data from automatic cameras and against snow depth data from measuring campaigns. This interpolation algorithm also included an altitudinal gradient of 5% per 100 m for solid precipitation (based on [17]). An overview of the parameter-specific data preprocessing and mapping methods used in this study is given in Table 2. The interpolation algorithms were implemented in MeteoIO, an open-source meteorological interpolation library developed by [4].

2.3.2. PREVAH

As mentioned in the model description, PREVAH has extensively been used for operational purposes. We therefore followed the standard meteorological input scheme (described in [35] and [36]), which is successfully being used in an operational context and to which the model has been calibrated. Meteorological data came from a Swiss-wide gridded database which is based on a large network of Swiss meteorological stations grouped into 23 sub-regions. In our case, the region "Reuss" had by far the strongest weight (6 stations provided hourly values of all parameters, 17 stations also provided all parameters 3 times a day, and 70 stations were used for daily precipitation data). Daily average values were used for all meteorological input parameters. Precipitation and sunshine duration were interpolated with an "inverse distance weighting" (IDW) algorithm. As mentioned in the model description [34], a calibrated de-biasing factor was also applied to precipitation. For all other meteorological parameters (relative humidity, air temperature, global radiation and wind speed) IDW was used in combination with an elevation dependent regression (detrended interpolation). All methods used in PREVAH are presented in detail by [34].

2.4. Climate change scenarios

2.4.1. Meteorological data

The recent European Union regional climate modeling initiative ENSEMBLES provided up-to-date climate predictions for two 30-year periods in mid and late 21st century [21]. Based on the emission scenario A1B, 10 model chains (different combinations of GCMs and RCMs) were used as ensemble input to the hydrological models. RCM output was statistically downscaled to generate

Table 2
List of meteorological variables, origin and pre-processing steps for ALPINE3D. For more details refer to [23].

Parameter	Meteorological stations used	Mapping method
Air temperature	Gütsch and Grimsel	Use hourly mean of both stations, force measured monthly lapse rate evaluated over 1981–2010
Precipitation	Gütsch (hourly) and Göscheneralp (daily sums)	Scale hourly Gütsch data to meet monthly sums measured at Göschenernalp, apply altitudinal gradient of 5% per 100m for solid precipitation, interpolation accounting for terrain curvature and slope
Wind speed	Gütsch	Scaled to fit the average wind speeds recorded at the 3 local weather stations over 3 years. Each local weather station was associated with one sub-catchment
Incoming short wave radiation	Gütsch	No external mapping, ALPINE3D includes shading and multiple scattering algorithms
Incoming long wave radiation	Gütsch	Computed from air temperature, relative humidity and incoming short wave radiation
Relative humidity	Gütsch and Grimsel	Same method as air temperature, but using dew point temperature for lapse rate approach

meteorological time series representative of future climate at locations of existing ANETZ climate stations (Fig. 2) using a delta change scheme detailed in [32,7]. These data were also used in other studies such as [5,9].

The hydrological models were run over the following three periods

1. Reference run (T0) – 1st October 1981–1st October 2010
2. Near future (T1) – 1st October 2021–1st October 2050
3. Far future (T2) – 1st October 2070–1st October 2099

where the reference period was given by the data availability from the ANETZ stations. For both PREVAH and ALPINE3D, temperature and precipitation projections were calculated using daily and station-specific temperature changes (ΔT), and precipitation scaling factors (ΔP) as shown in Fig. 2. Incoming long-wave radiation was recalculated based on air temperature changes (c.f. Table 1, ALPINE3D only). Relative humidity, wind speed and incoming short-wave radiation were left unchanged. For ALPINE3D, the delta change signal of Grimsel and Gütsch (refer to Fig. 1 for location) was used for ΔT and ΔP. The delta change signal from Göscheneralp was used solely for ΔP. For PREVAH, the delta change signal (ΔT and ΔP) from Grimsel only was applied to the reference dataset for the whole area.

Future climatic trends for the whole of Switzerland are presented by [7]. RCM data downscaled to represent future climate at Gütsch (Fig. 2) and Grimsel suggest warmer and dryer summers, as well as slightly wetter autumns. The mean yearly climatic changes expected at Gütsch as an average of all scenarios are $\{\Delta T = 1.23\,°C, \ \Delta P = 1.00\}$ for 2021–2050 and $\{\Delta T = 3.35\,°C, \Delta P = 0.99\}$ for 2070–2099. The differences in ΔT among scenarios are stronger in summer with up to 3 °C difference for the near future and 4.5 °C for the far future. A significant increase in temperature is predicted for the end of the century, with a stronger inter-scenario agreement than in the near future, especially in winter and spring. An important aspect is that the increase in temperature for both the near and far future periods differs from the current natural variability. This is in contrast with the predicted changes in precipitation which are, for both near and far future, in the range of natural climate variability. There is however a trend towards

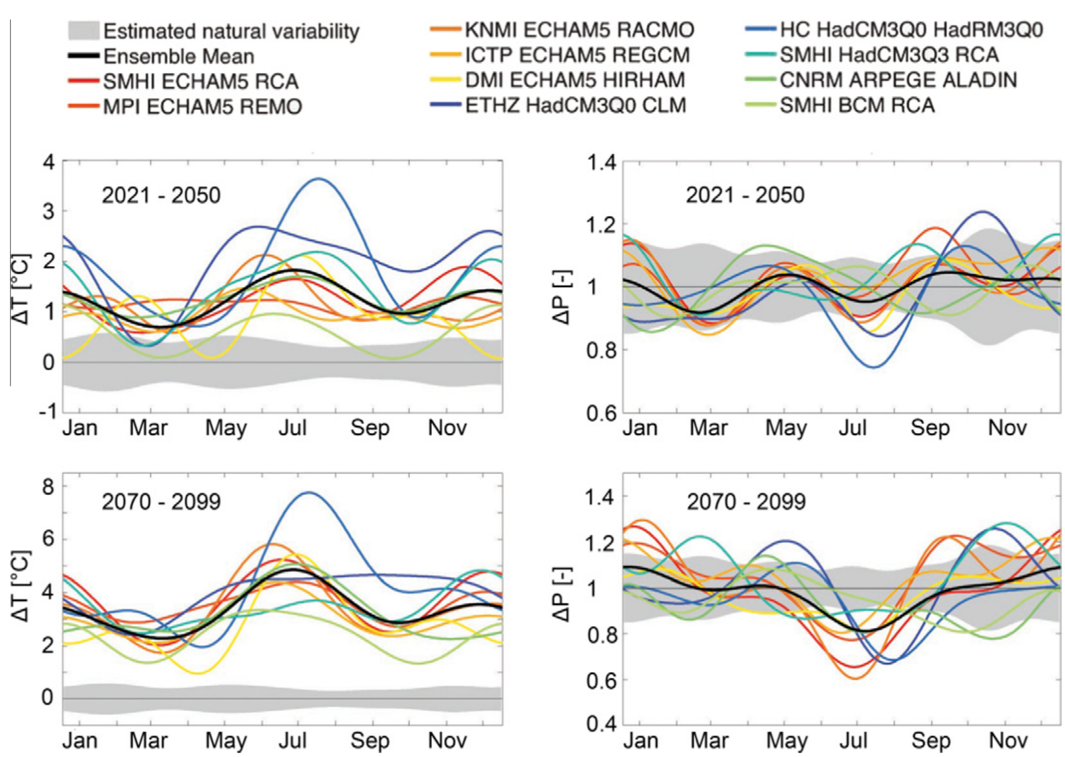

Fig. 2. Graphical representation of ΔT and ΔP for near and far future at the station Gütsch. Note that the grey bands represent an estimation of the past natural variability. The figure is sourced from the work of [7]. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

dryer summers, which becomes more consistent among scenarios at the end of the century. Wetter autumns are also predicted by most models but the inter-model variability is high in comparison to the mean predicted delta.

2.4.2. Glacier evolution

The evolution of glaciers is an important aspect in hydrological studies of glacierized catchments that cover time scales longer than a few years. Apart from accumulation and melt processes, glaciers also evolve due to ice flow. As both hydrological models used in this study do not account for glacier flow dynamics, we used glacier scenarios from separate calculations in order to regularly update the glacier extent in the hydrological models.

Glacier extent scenarios were provided by Paul et al. [28], who calculated the glacier evolution of Swiss glaciers in time steps of 5 years. Based on the shift of the equilibrium line altitude, future glacier geometries were calculated by means of hypsographic modeling (see [28] for details). The Göscheneralpsee catchment was 25% glacierized in 1985. Today's value of approximately 20% is predicted to shrink to 14% and 6% by respectively 2035 and 2085.

For ALPINE3D, each 30-year simulation period consisted of a succession of 6 independent six-year simulations including a spin-up period of 1 year. For instance, the reference period 1981–2010 was simulated as follows: (1) 1st October 1981–1st October 1987, (2) 1st October 1986–1st October 1992, and so on. Since glacier depth does not have an influence on the melt rates, the initial glacier depth was uniformly set to 50m (which is an estimation of the average present depth of the catchment's glaciers) so that the glacierized areas did not disappear within each six-year simulation step. Glaciers were initialized completely snow-free at the start of each 6 year simulation period. The spin-up period included in every modeling run allowed to re-create an accumulation area and to smooth the glacier edges before the results were evaluated.

PREVAH, on the other hand, assigns a different land use to the accumulation and ablation areas but requires no ice depth. The model assumes an infinite supply of ice, which does not allow the glacier surface to evolve within each modeling sub-step. The glacier areas were therefore, also with PREVAH, regularly updated. The update was performed every 5 years on October 1st. The three 30-year simulations were each preceded by a 6 year spin-up period.

3. Validation of the models

3.1. Dammareuss sub-catchment

As mentioned earlier, the performance of ALPINE3D was evaluated in a previous study for the 10 km^2 Dammareuss sub-catchment [23]. Their model results demonstrated too high glacier melt-rates in summer, likely due to unusually high turbulent heat fluxes. Glaciers are known to present specific micro-meteorological challenges. The existence of a consistent katabatic flow down glaciers has a strong effect on turbulent heat fluxes and, therefore, melting rates.

We analyzed possible sources of overestimated turbulent heat fluxes. These could be elevated wind speeds, too high surface roughness on the glacier, excessive ambient temperatures or an inappropriate formulation of the fluxes. An evaluation of the melting problem revealed, that excessive turbulent heat fluxes were most likely caused by the temperature input data being measured on exposed sunny terrain which becomes snow-free much earlier than most of the glacier surfaces. Unfortunately, no high-altitude temperature measurements were available for any length of time in the immediate vicinity.

ALPINE3D's current formulation of turbulent heat fluxes is based on the bulk aerodynamic method [20] with the possibility to add a stability correction to take into account the usually stable conditions found on a glacier surface [27]. It has been argued that the bulk aerodynamic formulation may not be very appropriate on glacier surfaces [12]. Grisogono and Oerlermans [10], Oerlermans and Grisogono [26] proposed a new parameterization of the turbulent heat fluxes on glacier surfaces, which was subsequently tested by Klok and Oerlermans [15] who studied the energy and mass balance of the Morteratsch glacier (Switzerland). Testing different formulations of turbulent heat fluxes was however not within the scope of this study. Instead we followed [31], who recently presented a temperature and relative humidity correction scheme for glaciers affected by katabatic flow. They proposed a bilinear temperature compensation factor based on the length of the glacier flow line (Eq. (1)).

$$\begin{aligned} &\text{if } T_a \geqslant T^* \Rightarrow T_g = T_1 + k_1(T_a - T^*) \\ &\text{if } T_a < T^* \Rightarrow T_g = T_1 - k_2(T^* - T_a) \end{aligned} \qquad (1)$$

where T_a denotes the ambient temperature measured at a meteorological station located outside of the glacier; T_g is the corrected temperature on the glacier surface; T^* is the threshold temperature above which katabatic flow becomes important; T_1, k_1 and k_2 are parameters of the bilinear parameterization. We implemented the temperature correction using an averaged coefficient based on the average length of the glaciers in our specific catchment. This temperature correction led to substantial improvement of glacier melt rates in summer but also to a slight delay in spring melt. This approach was adopted for the climate change simulations in this study, as runoff modeling was overall significantly improved.

Note that previous simulations with ALPINE3D by Magnusson et al. [23] had been run on a 50 m grid. Due to computational constraints we had to reduce the grid resolution in this study to 200 m to allow for a significant up-scaling in the spatial and temporal domain. To investigate the transferability of the work of Magnusson et al. [23] regarding model set-up and validation, we ran ALPINE3D with both 50 and 200 m grid resolution over the 2007–2010 period for the Dammareuss sub-catchment. The resulting runoff calculations were almost identical and the Nash Sutcliffe efficiency varied by less than 1%.

3.2. Entire catchment of Göschernalpsee

For model validation at the scale of the entire watershed, we used data of the inflow to the Göschernalpsee, which was measured by the hydropower operator during 1997–2010.

Both models reproduced qualitatively well flow variations on seasonal and decadal time scales (Table 3).

Table 3
Nash-Sutcliffe (NS) and benchmark efficiency (BE) for ALPINE3D and PREVAH.

Calibration interval	1997–2003		2004–2010		1997–2010		Evaluation PREVAH 1993–2010	
Indicator	NS	BE	NS	BE	NS	BE	NS	BE
ALPINE3D	0.80	0.16	0.82	0.29	0.85	0.19	–	–
PREVAH	–	–	–	–	–	–	0.91	0.49

The Nash-Sutcliffe (NS) coefficient of the average daily runoff over the 1997–2010 period is satisfactory for both models with 0.91 for PREVAH and 0.85 for ALPINE3D.

This coefficient is however bound to be satisfactory with such a long high-amplitude seasonal record. We therefore additionally used a benchmark efficiency (BE) indicator (e.g. [29,30]) to better assess model performance (Eq. (2)):

$$BE = 1 - \frac{\sum_t (Q_{\text{meas}}(t) - Q_{\text{mod}}(t))^2}{\sum_t (Q_{\text{meas}}(t) - Q_{\text{bench}}(t))^2} \quad (2)$$

where Q_{meas} is measured runoff; Q_{mod} is simulated runoff by the hydrological model; and Q_{bench} is runoff predicted by the benchmark model. The benchmark model used here is rather stringent: the inter-annual mean value for every calendar day over the calibration period (referred to as calendar day benchmark model in [29]).

With ALPINE3D, the available runoff record was split into 2 calibration/validation intervals (1997–2003, 2004–2010) to assess the reliability of our calibration procedure. We then calibrated on the whole period of 1997–2010 to yield the best possible set of parameters for the climate change simulations (c.f. Section 4). As described in Section 2.2.2, the calibration with PREVAH was done independently of this study, using all available runoff data for the region during the 1993–2010 period (see [35]). The NS and benchmark test results are presented in Table 3. We consider the achieved positive BE values to be satisfactory as this is a much more stringent test compared to the classical NS coefficient. PREVAH performed better than ALPINE3D in this particular case, probably due to a more complex and data intensive calibration procedure.

Although both hydrological models demonstrated good results overall, there are small systematic seasonal deviations from the observed inflows (Fig. 3, lower panel). The seasonality of these deviations differed significantly between the two models.

ALPINE3D underestimated runoff at the beginning of snowmelt (May). This is compensated by slightly excessive runoff towards the end of the seasonal increase in summer (1st half of July). This deviation is due to the timing of snowmelt, which is on average 5 days too late. As mentioned above we identified the delay to be caused by the temperature correction following [30], being too large for spring conditions. During the rest of the year (especially September to April), ALPINE3D results are in very good agreement with the measured runoff.

On the other hand, PREVAH underestimated runoff when glacial melt contributed to most of the total runoff (mid-July to early September). This deficit is compensated by excessive runoff during the months of October and November. The difference in total runoff between the two models is 2.5% during 1997–2010 and only 0.6% over the entire reference period of 1981–2010.

4. Climate change simulations: results and discussion

4.1. Changes of the seasonal runoff dynamics

Fig. 4 presents the seasonal runoff projections of the two hydrological models for the near and the far future periods. Each plot shows the seasonal runoff dynamics averaged over 30 years of the reference period (black line), according to different climate scenarios (colored lines), and respective percentile ranges for the spread between individual years (dashed lines). As PREVAH is computationally very efficient we could perform 21 simulation runs over 30 years each (i.e. 10 different climate projections for 2 future periods plus 1 reference run). However, with the much higher computational demand of ALPINE3D we were only able to realize simulations for 3 out of 10 climate projections (7 runs over 30 years in total). We selected the projections to represent an average (CNRM ARPEGE ALADIN), a warmer (ETHZ HadCM3Q0 CLM) and a colder (SHMI BCM RCA) than average scenario. We later refer to these scenarios as respectively CNRM, ETHZ and SHMI.

The results of both hydrological models show many similarities regarding the seasonal pattern of runoff (Figs. 4 and 5). Although discharge shows significant variations among years, the reservoir inflow currently peaks in early July on average. Table 4 presents the evolution of key parameters regarding amplitude and timing of median runoff, as predicted by both models for the three common scenarios. Note that our use of "peak-flow" and "peak-day" in the following interpretation is an approximation as a 30-day moving average was applied to all runoff data. Peak-day discharge is also not always the best indicator of temporal shifts as the peaks can be flat for some scenarios. We therefore also use the center of mass (COM), which is an integrated indicator for evidencing

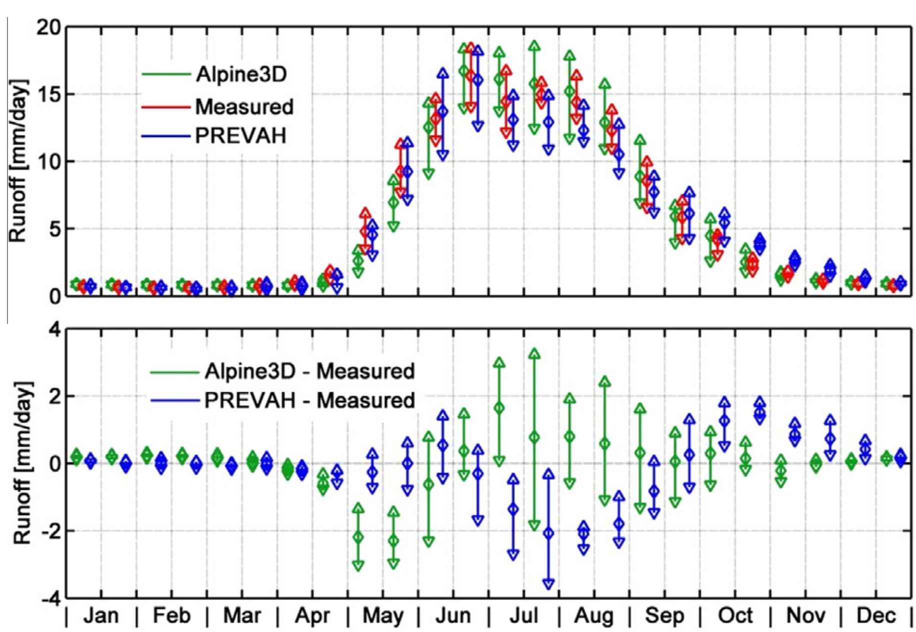

Fig. 3. Boxplot (Q25%, Q50%, Q75%), over the 1997–2010 period, of the mean bi-weekly differences between modeled (PREVAH and ALPINE3D) and measured runoff during the year. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

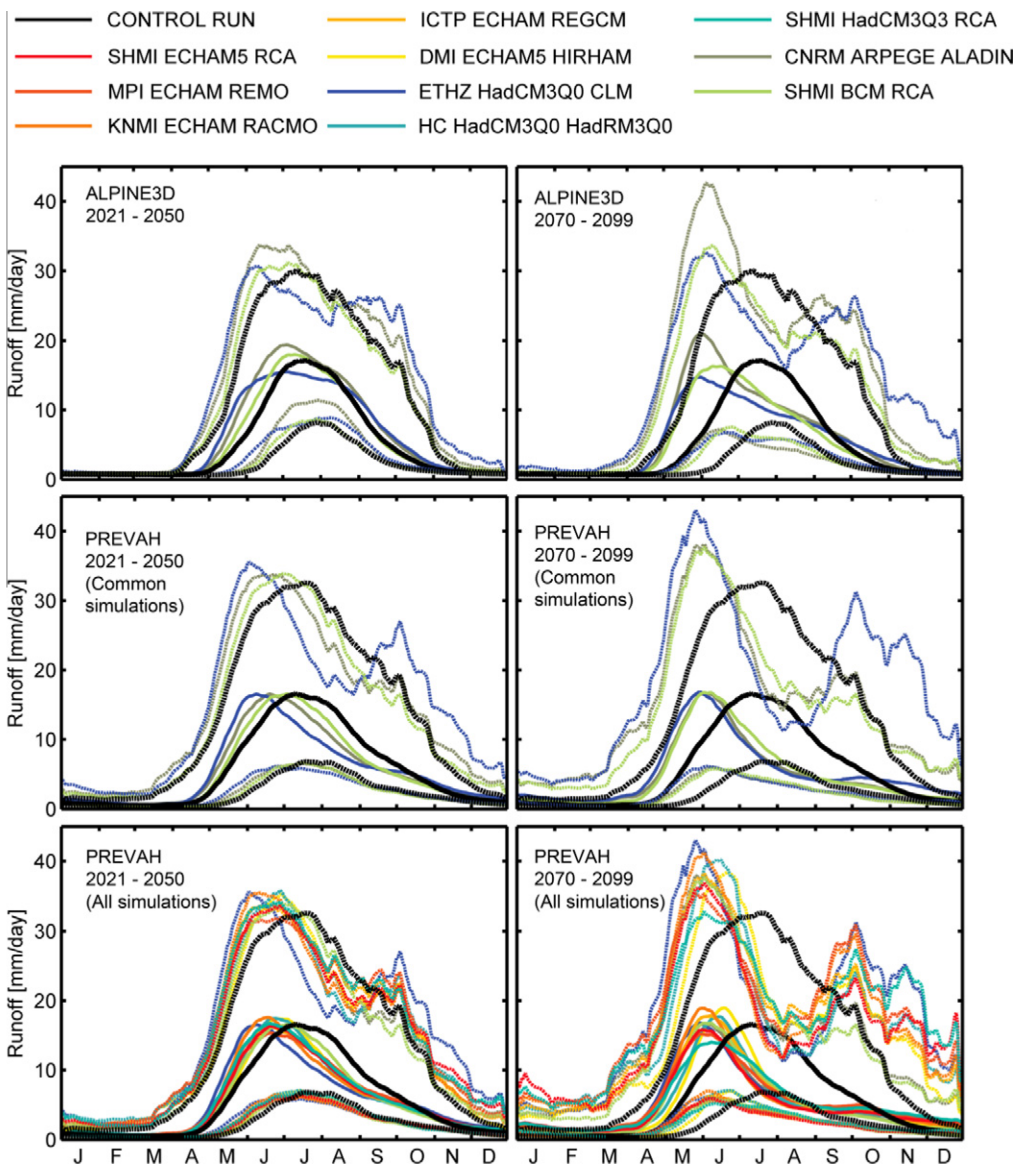

Fig. 4. Results of PREVAH and ALPINE3D for the reference and both future periods. Solid lines represent the median runoff and the dashed lines its variability (Q2.5% and Q97.5%). A 30-day averaging filter was applied. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

changes in hydrological regime. It demonstrates a more homogeneous shift than the peak-day for both models. In Table 4, PREVAH consistently predicts stronger shifts in COM than ALPINE3D. On average, the projections do not suggest a considerable change in peak-flow for the median runoff. There is however some variability between the different scenarios and particularly between the hydrological models. The predicted changes in peak-flow for median runoff are indeed larger with ALPINE3D than with PREVAH.

Combined with a shift in the start of the melting season, the spring increase in snowmelt runoff will also develop faster, which may be an interesting aspect for flood prevention and reservoir management.

Late summer flow is predicted to fall significantly below current levels for both future periods with PREVAH but only for the far future with ALPINE3D. We will discuss the respective differences between the projections of both models in detail further below (c.f. Fig. 6). A marked decrease in the late summer flows can be relevant for water supply issues and poses a threat to regions that critically depend on delayed runoff from snow and ice melt [25].

Fig. 5 displays the changes in the seasonal runoff dynamics as projected by the two hydrological models. This plot allows to discuss the differences in the model projections at greater detail. While the seasonality of the predicted changes is generally in good agreement, ALPINE3D however consistently predicts higher runoff than PREVAH during high flow periods (April to October). This finding is particularly pronounced with the CNRM ARPEGE ALADIN climate scenario, which represents a warmer than average scenario. Interestingly, only PREVAH predicts a reduction in runoff during summer (July-August) for the near future scenarios.

The greatest differences between the models occur during the summer months, which are dominated by glacier melt. This result and its potential causes are analyzed in further detail in Section 4.3.

4.2. Evolution of high and low flow periods

The expected changes in the inflow of the reservoir must be analyzed in the context of the natural variability between years (dashed lines in Fig. 4). Here, we describe high and low flow periods, namely the peaks of Q2.5% and Q97.5% flows, which are events with a return period of 40 years.

The peak summer runoff during high and low flow years is approximately twice as high or less than half as high, as in average

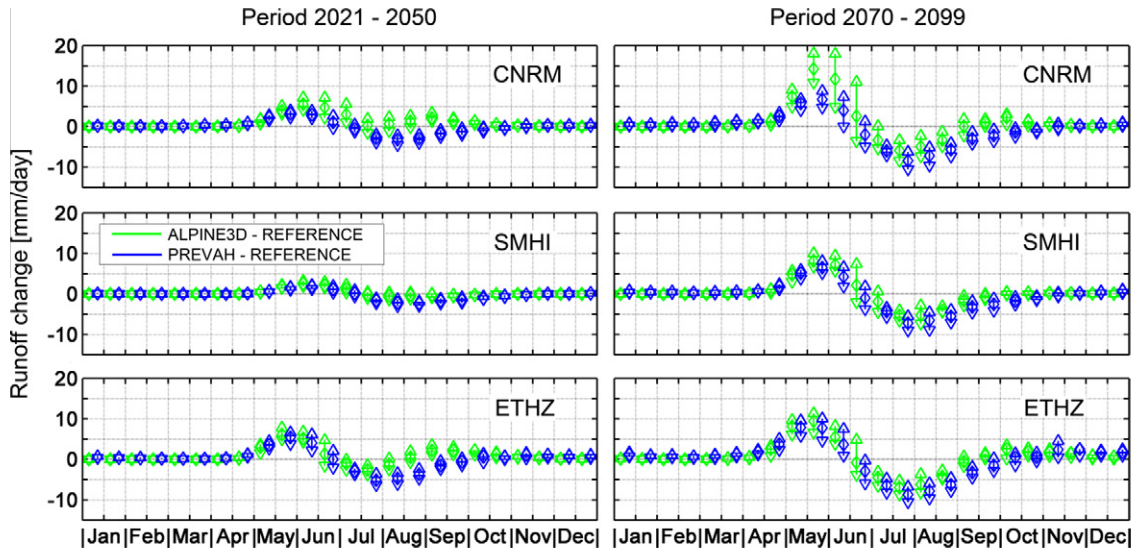

Fig. 5. Boxplot (Q25%, Q50% and Q75%) of the mean bi-weekly differences between the reference and both future periods for scenarios CRNM ARPEGE ALADIN, SMHI BCM RCA and ETHZ HadCM3Q0 CLM. ALPINE3D results are in green and PREVAH in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Shift in peak-day, shift in centre of mass (COM) and peak-flow variation for median runoff (Q50%). T1 and T2 are respectively the near and far future periods.

Parameter	Model	CNRM T1	CNRM T2	ETHZ T1	ETHZ T2	SHMI T1	SHMI T2
Shift in peak-day (days)	A3D	−16	−51	−16	−51	−9	−34
	PREVAH	−21	−40	−32	−42	−6	−33
Shift of COM (days)	A3D	−6	−24	−6	−19	−5	−20
	PREVAH	−14	−34	−18	−34	−9	−30
Peak-flow variation (%)	A3D	13.4	13.4	−9.3	−13.8	5.0	−4.7
	PREVAH	−0.3	−0.3	−0.3	1.5	−0.1	1.1

years. In comparison, the predicted changes are relatively small, so that the median future annual runoff cycles lies well within the limits of the current variability.

Both models provide remarkably similar results for median runoff as well as low and high percentile values (Q2.5% and Q97.5%) for the reference period (c.f. Fig. 4). This finding indicates that both models show an equivalent sensitivity in the hydrological response to the natural variability of today's climate. Predicted future peak-flow for Q2.5% and Q97.5% runoff are presented in Table 5. The variations of peak-flow for Q97.5% are all positive but vary significantly among hydrological models and scenarios. The strongest increases in the peak-flow of Q97.5% runoff happen in the far future with both hydrological models but not with the same scenario. ALPINE3D predicts a 41.4% increase with CNRM ARPEGE ALADIN, whereas PREVAH predicts a 31.8% increase with ETHZ HadCM3Q0 CLM. This implies that the magnitude of future flood situations will probably increase. The uncertainty related to both hydrological and climate models is however too high to quantify this potential increase accurately.

The variations of peak-flow for Q2.5% are all negative except with ALPINE3D for all of the near future scenarios. The predicted decrease for the far future is quite consistent between hydrological and climate models as it ranges between −7.7% and −17.3%. We can therefore expect dry years in the far future to become drier than in the past.

Another trend that is clearly noticeable is the apparition of a marked autumn peak in the 97.5% percentile, for both periods with PREVAH and only for the far future with ALPINE3D. This is caused by higher future precipitation in autumn combined with lower late-summer flows due to disappearing glaciers. A similar projection had already been found by Horton et al. [13] and suggests a potential future change in the discharge regime classification of the studied catchments, from nivo-glacial to nivo-meridional.

It must be noted, that one of the limitations of the delta-change approach used in this study is that the future climate variability remains unchanged relative to the reference data. This applies to the inter-annual, seasonal, and daily variability. Such limitation has a direct impact on the ability of the models to quantify the spread between high and low flows for the future.

4.3. Variation in annual discharge

As reported above, the greatest differences between the projections of the two hydrological models relate to the season that is dominated by glacier melt. To further analyze the temporal dimension of the differences in models behavior, we calculated the changes in runoff relative to the reference period separately aggregated for four seasons (Fig. 6). The three-month aggregation periods were chosen according to the seasonality of predicted runoff changes (c.f. Fig. 5) with a clear trend reversal at the end of June. For a clearer presentation, we focused on the ETHZ-HadCM3Q0-CLM scenario, which represents the average case out of those three climate scenarios that were used as input for both hydrological models.

The evolution of mean annual runoff changes for the two future periods is shown by the black lines in Fig. 6. ALPINE3D predicts a considerable increase in annual runoff for the near future scenario. This increase extends well into the far future period but a gradual diminution finally brings the annual runoff below the reference during the last decade of this century. The predicted mid-term in-

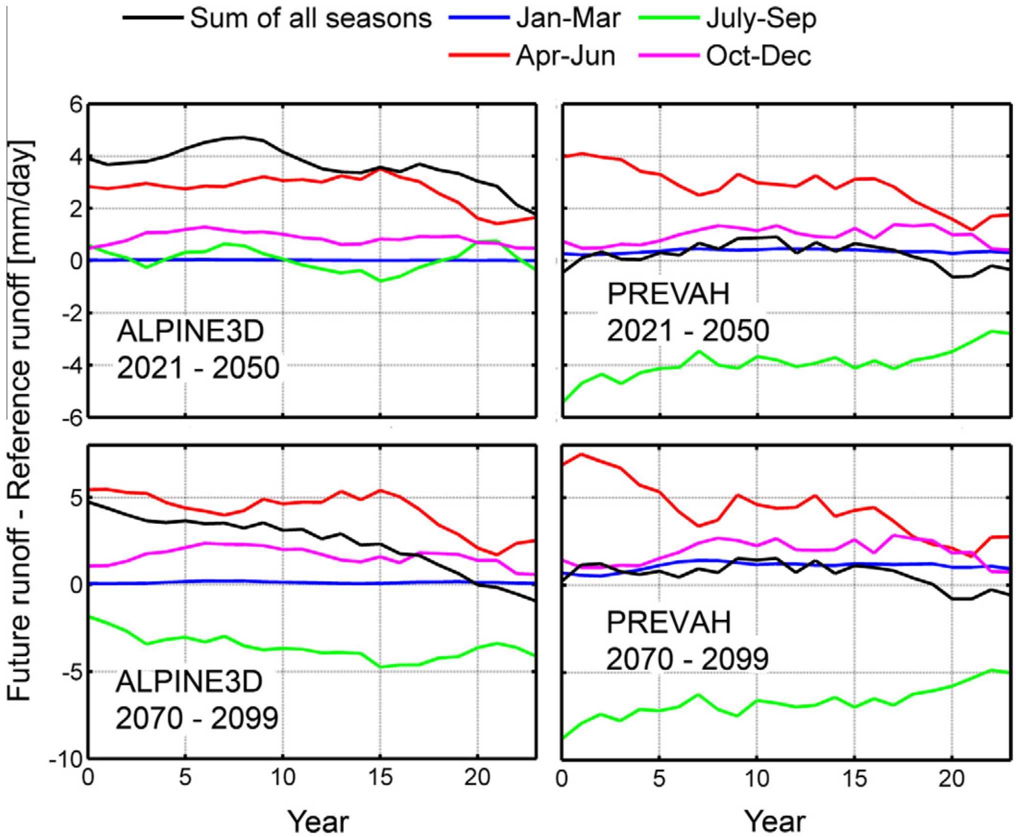

Fig. 6. Variations in seasonal runoff changes during both future periods, as predicted by ALPINE3D and PREVAH. A 5-year running filter is applied. Note the different scale in *y*-axis between the upper and lower panels. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

Table 5
Peak-flow variation (%) for Q2.5% and Q97.5% runoff. Values are expressed as a percentage change from the reference period. T1 and T2 are respectively the near and far future periods.

Scenario	CNRM T1		CNRM T2		ETHZ T1		ETHZ T2		SHMI T1		SHMI T2	
Quantile	Q2.5	Q97.5	Q2.5	Q97.5	Q2.5	Q97.5	Q2.5	Q97.5	Q2.5	Q97.5	Q2.5	Q97.5
A3D	39.0	12.1	−11.9	41.4	8.2	1.9	−17.3	8.5	5.8	3.4	−7.7	11.6
PREVAH	−3.3	3.8	−13.0	16.9	−10.2	9.1	−10.0	31.8	−1.9	3.9	−15.2	15.7

crease (near future scenario) averages at 16% change in total annual volume. To the contrary, PREVAH does not predict any considerable changes in cumulated runoff, for neither of the 2 future periods.

The separation of the same data into seasonal sums reveals, that both models agree fairly well with regards to three out of four aggregation periods. Changes for January to March remain on average below 1 mm d^{-1} for both periods and both models. October to December runoff will increase by around 1 mm d^{-1} for the near and 2 mm d^{-1} for the far future scenario. Likewise, the increase in snowmelt-related runoff during April to June amounts to about 3 and 4 mm d^{-1} for the near and far future respectively.

As already evidenced in Section 4.1, the model differences in total annual runoff are almost solely based on different predictions for the summer months July to September. This season will be even more dominated by glacier melt in the future than today, as summer precipitation is expected to decrease (see Fig. 2). The physically-based model ALPINE3D showed a pronounced response to albedo changes at the glacier surface, which will be longer exposed to intense solar radiation in the future as the seasonal snow cover disappears earlier. The model indeed showed a marked increase in runoff from July to September for as long into the future as the shrinking glacier extent did not compensate the above effect. PREVAH, on the other hand, showed less sensitivity of glacier melt rates to the climate change scenarios. PREVAH conceptually captures albedo changes based on the climatology it has been calibrated for. Both the Radiation Melt Factor and the Temperature Melt Factor (see Section 2.2.3) are approximately 25% higher for ice as for snow in our simulations. These values stem from the calibration procedures described in [35,36] that were partly adapted for the specific needs of this study. The melt factors in PREVAH were thus calibrated for an ablation period which is relatively short and centered around late-summer. In the future however, glacier ice will be exposed sooner and longer to solar radiation. This may lead to a higher share of the net short wave radiation in the energy-balance, potentially requiring an increase of the present-day melt factors for ice in PREVAH. The importance of the net shortwave radiation in the total energy-balance budget of a melting glacier was already pointed out by Klok and Oerlermans [15]. For both models, the different sensitivities of glacier melt rates to the climate change scenarios seem to explain a considerable part of the model differences in total annual runoff. As glacier extent reduces significantly between the near and far future periods, such differences are more pronounced in the near future. This is clearly visible in Fig. 6.

Table 6
Mean shift and spread of the center of mass (COM) between future and reference median runoff (expressed in days). Only the three scenarios common to both models are used. T1 and T2 are respectively the near and far future periods.

Period	T1		T2	
Shift of COM	Mean	Spread	Mean	Spread
ALPINE3D	5.7	1	21.0	5
PREVAH	13.7	9	32.7	4

4.4. Modeling uncertainties

The spread between the hydrological projections of the 10 climate change scenarios is an indication of the uncertainties associated with climate modeling. However, only with PREVAH are the 10 scenarios available (see Fig. 4). In Table 6 we present in detail the predicted shifts in COM, taking into account those three scenarios that are common to both models. Overall, the spread in COM between the scenarios is much smaller than the mean shift in COM. PREVAH presents noticeably more spread than ALPINE3D, but only for the near future projections. On the other hand, the differences between the mean shifts in COM as predicted by PREVAH versus ALPINE3D are comparable to the spread in COM among climate change scenarios. These results indicate that uncertainties attributed to the hydrological models may be on the same order of magnitude as those of climate change models. Further such studies would certainly help disentangling uncertainties resulting from coupled climate and hydrological models.

5. Conclusions

We presented a climate change study in a 95 km^2 glacierized catchment in the Swiss Alps. The originality of the study resides in the fact that two different modeling approaches were used: (1) a detailed energy-balance model (ALPINE3D) primarily designed for snow simulations and (2) a conceptual runoff model system (PREVAH), including a distributed temperature-index ice-melt model. This had been done for data representing current hydrometeorological conditions but seldom, to this extent, on future predictions.

Applying a process-oriented distributed model such as ALPINE3D in complex terrain requires significantly more effort in comparison to conceptual modeling approaches. In a preceding study, [23] evaluated the performance of ALPINE3D for the Dammareuss catchment, a sub-catchment which represents approximately 10% of the study area of this study. They spent a considerable effort into distributing available meteorological station data to the model grids as forcing data. This resulted in an optimized methodology for the use of ALPINE3D in this region, which constituted an important foundation for this study.

On the other hand, PREVAH has extensively been used in operational hydrology throughout the Swiss Alps. Parameter values used in this study are based on the substantial effort that had previously been put into calibrating it at a regional level for operational purposes.

The climate change projections of both hydrological models showed many similarities regarding the seasonal pattern of future runoff. The simulations suggest a shift of spring peak-flow by approximately 3 and 6 weeks for the periods 2021–2050 and 2070–2099, respectively. On average, the projections do not suggest a considerable change in peak-day discharge for median runoff. There is however some uncertainty among the different scenarios and hydrological models. The current natural variability in runoff between years is considerable, where high flow years can produce cumulative summer runoff four times higher than in low flow years. Our calculations suggest that high flow years will consistently bring higher peak-flows, while dry periods should become drier in the future. The variability in runoff between years should therefore increase. However, limitations of the delta-change approach used here do not allow further quantification.

Although both hydrological models produced results consistent in many aspects, they differed notably regarding predictions of annual runoff changes. Only ALPINE3D predicted a considerable increase in annual runoff for the near future scenario, which extends well into the far future period but finally ceases during the last decade of this century. To the contrary, PREVAH did not provide evidence for future changes in mean annual runoff. We found this difference to be attributed to the glacier melt season. Only the physically based model ALPINE3D showed a pronounced sensitivity of glacier melt to the climate change scenarios. This resulted in increased runoff during late-summer for as long into the future as the shrinking glacier extent did not compensate the elevated melt rates. This finding suggests that climate change projections for runoff from partly glacierized watersheds require particular attention to the glacier melt component. Both models showed a similar performance when reproducing the seasonal runoff dynamics during the reference period but drifted apart when projecting into the future.

In conclusion, our multi-model approach allowed a detailed insight in the uncertainties associated with model projections of future runoff dynamics based on climate change scenarios. While ensemble technique is typically used to quantify uncertainties related to climate change scenarios, the approach neglects any uncertainty associated with the hydrological modeling. In this case study, the two hydrological models used entailed similar predictions of the runoff dynamics in many aspects but disagreed regarding future glacier melt rates leading to a considerable difference in annual runoff figures. We suggest this multi-model approach as a way of improving our understanding of uncertainties related to climate change projections with hydrological models.

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References

[1] Addor N, Jaun S, Fundel F, Zappa M. An operational hydrological ensemble prediction system for the city of Zurich (Switzerland): skill, case studies and scenarios. Hydrol Earth Syst Sci 2011;15:2327–47. http://dx.doi.org/10.5194/hess-15-2327-2011.
[2] Barnett TP, Adam JC, Lettenmaier DP. Potential impact of a warming climate on water availability in snow-dominated regions. Nature 2005;438(17):303–9. http://dx.doi.org/10.1038/nature04141.
[3] Bavay M, Lehning M, Jonas T, Löwe H. Simulations of future snow cover and discharge in Alpine headwater catchments. Hydrol Process 2009;23:95–108. http://dx.doi.org/10.1002/hyp.7195.
[4] Bavay M, Egger T. Meteoio: a meteorological data pre-processing library for numerical models. Geophys Res Abstr EGU General Assembly 2011;13(EGU2011-11653). <http://slfsmm.indefero.net/p/meteoio>.
[5] Bavay M, Grünewald T, Lehning M. Response of snow cover, glaciers, and runoff to climate change in high Alpine catchments of Eastern Switzerland. Adv Water Resour [submitted for publication].

[6] Bernasconi SM et al. Chemical and biological gradients along the Damma glacier soil chronosequence, Switzerland. Vadose Zone J 2011;10:867–83. http://dx.doi.org/10.2136/vzj2010.0129.
[7] Bosshard T, Kotlarski S, Ewen T, Schär C. Spectral representation of the annual cycle in the climate change signal. Hydrol Earth Syst Sci 2011;15:2777–88. http://dx.doi.org/10.5194/hess-15-2777-2011.
[8] Bougamont M, Bamber JL, Ridley JK, Gladstone RM, Greuell W, Hanna E, Payne AJ, Rutt I. Impact of model physics on estimating the surface mass balance of the Greenland ice sheet. Geophys Res Lett 2007;34:L17501. http://dx.doi.org/10.1029/2007GL030700.
[9] Farinotti D, Usselmann S, Huss M, Bauder A, Funk M. Runoff evolution in the Swiss Alps – projections for selected high-alpine catchments based on ENSEMBLES scenarios. Hydrol Process, in press. http://dx.doi.org/10.1002/hyp.8276.
[10] Grisogono B, Oerlermans J. A theory for the estimation of surface fluxes in simple katabatic flows. Quart J Roy Meteorol Sci 2001;127:2725–39.
[11] Gurtz J, Zappa M, Jasper K, Lang H, Verbunt M, Badoux A, Vitvar T. A comparative study in modeling runoff and its components in two mountainous catchments. Hydrol Process 2003;17:297–311. http://dx.doi.org/10.1002/hyp.1125.
[12] Hock R. Glacier melt: a review of processes and their modeling. Prog Phys Geog 2005;29(3):362–91.
[13] Horton P, Schaefli B, Mezghani A, Hingray B, Musy A. Assessment of climate-change impacts on alpine discharge regimes with climate model uncertainty. Hydrol Process 2006;20:2091–109. http://dx.doi.org/10.1002/hyp.6197.
[14] Huss M, Farinotti D, Bauder A, Funk M. Modeling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrol Process 2008;22:3888–902. http://dx.doi.org/10.1002/hyp.7055.
[15] Klok EJ, Oerlermans J. Model study of the spatial distribution of the energy and mass balance of Morteratschgletscher, Switzerland. J Glaciol 2002;48(163):505–18.
[16] Koboltschnig GR, Schoener W, Zappa M, Kroisleitner C, Holzmann H. Runoff modelling of the glacierized Alpine Upper Salzach basin (Austria): multi-criteria result validation. Hydrol Process 2008;22:3950–64. http://dx.doi.org/10.1002/hyp.7112.
[17] Kormann C. Untersuchungen des Wasserhaushaltes und der Abflussdynamik eines Gletschervorfeldes. Diplomarbeit 2009, Institut für Hydrologie und Meteorologie, Technische Universität Dresden.
[18] Kuonen P, Bavay M, Lehning M. POP-C++ and ALPINE3D: petition for a new HPC approach. In: Asimakopoulou E, Bessis N, editors. Advanced ICTs for disaster management and threat detection: collaborative and distributed frameworks. IGI Global; 2010:237–61. http://dx.doi.org/10.4018/978-1-61520-987-3.ch015.
[19] Lehning M, Bartelt P, Brown B, Fierz C. A physical SNOWPACK model for the Swiss avalanche warning. Part I: Meteorological forcing, thin layer formation and evaluation. Cold Reg Sci Technol 2002;35:169–84.
[20] Lehning M, Völksch I, Gustafsson D, Nguyen TA, Stähli M, Zappa M. ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology. Hydrol Process 2006;20:2111–28. http://dx.doi.org/10.1002/hyp.6204.
[21] Lindon P, Mitchell J. ENSEMBLES: Climate change and its impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK; 2009. 160pp.
[22] Magnusson J, Jonas T, López-Moreno I. Snow cover response to climate change in a high alpine and half-glacierized basin in Switzerland. Hydrol Res 2010;41:230–40. http://dx.doi.org/10.2166/nh.2010.115.
[23] Magnusson J, Farinotti D, Jonas T, Bavay M. Quantitative evaluation of different hydrological modeling approaches in a partly glacierized Swiss watershed. Hydrol Process 2011;25:2071–84. http://dx.doi.org/10.1002/hyp.7958.
[24] Marks D, Domingo J, Susong D, Link T, Garen D. A spatially distributed energy balance snowmelt model for application in mountain basins. Hydrol Process 1999;13:1935–59.
[25] Nolin AW, Phillippe J, Jefferson A, Lewis SL. Present-day and future contributions of glacier runoff to summertime flows in a Pacific Northwest watershed: Implications for water resources. Water Resour Res 2010;46(W12509):1–14. http://dx.doi.org/10.1029/2009WR00896.
[26] Oerlermans J, Grisogono B. Glacier winds and parameterization of the related surface heat fluxes. Tellus 2002;54A:440–52.
[27] Paterson WSB. The Physics of Glaciers. 3rd ed. Pergamon; 1994.
[28] Paul F, Maisch M, Rothenbühler C, Hoelze M, Haeberli W. Calculation and visualization of future glacier extent in the Swiss Alps by means of hypsographic modeling. Global Planet Change 2007;55:343–57.
[29] Schaefli B, Gupta HV. Do Nash values have value? Hydrol Process 2007;21:2075–80. http://dx.doi.org/10.1002/hyp. 6825.
[30] Seibert J. On the need for benchmarks in hydrological modelling. Hydrol Process 2001;15:1063–4. http://dx.doi.org/10.1002/hyp.446.
[31] Shea JM, Moore RD. Prediction of spatially distributed regional-scale fields of air temperature and vapor pressure over mountain glaciers. J Geophys Res 2010;115:D23107. http://dx.doi.org/10.1029/2010JD014351.
[32] Swiss Climate Change Scenarios CH2011. Zurich, Switzerland: C2SM, MeteoSwiss, ETH, NCCR Climate and OcCC; 2011. ISBN 978-3-033-03065-7. <http://www.ch2011.ch/>.
[33] Swiss land use statistics 1992/97 – Nomenclature NOAS92: basic categories and aggregations. Swiss Federal Statistical Office; 1992. <http://www.bfs.admin.ch>.
[34] Viviroli D, Zappa M, Gurtz J, Weingartner R. An introduction to the hydrological modeling system PREVAH and its pre- and post-processing-tools. Environ Modell Softw 2009;24:1209–22.
[35] Viviroli D, Zappa M, Schwanbeck J, Gurtz J, Weingartner R. Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part I: Modelling framework and calibration results. J Hydrol 2009;377:191–207.
[36] Viviroli D, Mittelbach H, Gurtz J, Weingartner R. Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalization and flood estimation results. J Hydrol 2009;377:208–25.
[37] Zappa M, Pos F, Strasser U, Warmerdam P, Gurtz J. Seasonal water balance of an Alpine catchment as evaluated by different methods for spatially distributed snowmelt modelling. Nord Hydrol 2003;34(3):179–202.
[38] Zappa M, Kan C. Extreme heat and runoff extremes in the Swiss Alps. Nat Hazards Earth Syst Sci 2007;7:375–89.
[39] Zappa M, Jaun S, Germann U, Walser A, Fundel F. Superposition of three sources of uncertainties in operational flood forecasting chains. Atmos Res 2011;100:246–62. http://dx.doi.org/10.1016/j.atmosres.2010.12.005.
[40] Zhang S, Ye B, Liu S, Zhang X, Hagemann S. A modified monthly degree-day model for evaluation glacier runoff changes in China. Part I: Model development. Hydrol Process 2011. http://dx.doi.org/10.1002/hyp.8286.