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Hydrological modelling and future runoff of the Damma Glacier CZO watershed using SWAT. Validation of the model in the greater area of the Göscheneralpsee, Switzerland

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Abstract. In this study, we investigated the application of the Soil Water and Assessment Tool (SWAT) for the simulation of runoff in the partly glacierised watershed of the Damma glacier Critical Zone Observatory (CZO), Switzerland. The model was calibrated using daily time steps for the period of 2009–2011, while two different approaches were used for its validation. Initially the model was validated using daily data for the years 2012–2013. Subsequently, the calibrated version of the model was applied on the greater area that drains to the hydropower reservoir of the Göscheneralpsee and includes the Damma glacier watershed, using inflow data. This validation approach can help in assessing model uncertainty under changing land use and climate forcing. Model performance was evaluated both visually and statistically and it was found that even though SWAT has rarely been used in high alpine and glacierised areas and despite the complexity of simulating the extreme conditions of Damma glacier watershed; its performance was very satisfactory. Our novel validation approach proved to be successful since the performance of the model was similarly good when applied for the greater catchment feeding Göscheneralpsee. Finally, we investigated the response of the two regions, Damma glacier and its greater area, to climate change using SWAT and results were compared to a previous study using the models PREVAH and ALPINE 3D. It confirmed that SWAT can predict changes in future runoff and peak flow in alpine areas with the same accuracy as more demanding models such as ALPINE 3D and PREVAH. This study demonstrates the applicability of SWAT in high elevation, snow and glacier dominated watersheds and in quantifying the effects of climate change on water resources.

1 Introduction

The use of calibrated watershed models enables researchers and stakeholders to assess the impact of natural and management induced environmental changes and, as many studies have pointed out, is of high importance (Arnold et al., 1998;Abbaspour et al., 2007). However watershed modelling in alpine areas is challenging due to the rough terrain, heterogeneous land cover, extreme climatic conditions and glacier dynamics (Viviroli and Weingartner, 2004;Rahman et al., 2013). These can also be the factors that increase the inherent uncertainties in watershed models (Kobierska et al., 2013).

Modelling the impact of climate change in future runoff provides crucial information for the assessment of water resources, water quality, and aquatic ecosystems. However, the uncertainties at this stage of modelling include uncertainties related to climate change scenarios and therefore, in order to reduce the uncertainty in the climate

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analysis, it is important to reduce the uncertainties related to the hydrological model by well-adjusted calibrated parameters and validation (Farinotti et al., 2012b).

The Soil and Water Assessment Tool (SWAT) developed by the USDA Agricultural Research Service (ARS) is a public domain and open source integrated model and has been used worldwide for various applications. As a semi-distributed model, it allows the spatial variation of the parameters by dividing the basin into a number of sub-basins (Arnold et al., 1998;Srinivasan et al., 1998). Its main advantages are that its structure is physically based, since it considers orographic effects, but less demanding on input data than the fully distributed models. SWAT model is equipped with a snow-melt algorithm based on a simple temperature-index approach, which, although simple, is proved to be very effective in numerous studies (Hock, 2003) especially when net solar radiation is the dominant driving energy for snowmelt (Debele et al., 2010).

SWAT has been widely used in many studies for the simulation of runoff and nutrient cycling in agricultural and forested sites. However, it has rarely been used for high alpine areas where runoff is dominated by snow and glacier melt. In this study we used SWAT to simulate the runoff from the partly glacierised Damma glacier watershed, Switzerland, which is characterised by strong daily and seasonal fluctuations due to snowmelt in May and June and glacier melt later in summer. Calibration was conducted using meteorological data for the years 2008–2011 and was validated for the years 2012–2013. Furthermore, we investigated the possibility to validate the model in the greater area that feeds the Göscheneralpsee and includes the Damma glacier watershed with a longer meteorological record. Finally, we investigated the impact of climate change in future runoff running 6 different future scenarios.

2 Study Site

The Damma glacier watershed (Fig. 1) situated in the central Alps in Switzerland and is one of the Critical Zone Observatories established within the European project SoilTrEC (Banwart et al., 2011). It is located at an altitude between 1790m and 3200 m above sea level and has a typical alpine climate with an average yearly temperature of 1°C and precipitation 2400mm per year (Kobierska et al., 2013). Damma glacier covers 50% of the watershed and due to climate change retreats at an average rate of 10m per year in the last 90 years. However, during 1920–1928 and 1970–1992 the recession was interrupted and the glacier re-advanced, which resulted in two moraines (Kobierska et al., 2011). After the retreat of the glacier a soil chronosequence is developed, which has a total length of 1km (Kobierska et al., 2013;Bernasconi et al., 2008;Bernasconi et al., 2011). The bedrock is coarse-grained granite of the Aare massif and is composed of quartz, plagioclase, potassium feldspar, biotite and muscovite (Schaltegger, 1990). Our study site was extensively described in Bernasconi *et al.* (2011).

The Göscheneralpsee (Fig. 2) is a hydropower reservoir of a volume of 75 million m^3. A total surface area of 95km^2 drains in the reservoir and is 20% glacier–covered. It includes the Damma glacier watershed but also the Chelen glacier watershed and the runoff of two neighbouring watersheds (Voralptal and Tiefen glacier), which is redirected in the reservoir through two tunnels. The site is described extensively in Kobierska *et al.* (2013).

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3 Methods and Data

3.1 SWAT model

In this study, we used SWAT 2012 coupled with the ArcView SWAT interface a GIS-based graphical user interface (Di Luzio et al., 2002) that enables the delineation of the watershed, definition of subbasins, and initial parameterisation. It is a semi-distributed, time continuous watershed simulator operating on a daily time step.

Each watershed is divided into subbasins, for which slope, river features, and weather data are considered. Furthermore, the watershed is divided into hydrologic response units (HRUs), which are small surface units with distinctive soil-landuse combinations and necessary to capture spatially explicit processes. Each process is simulated for each HRU and then summed up for the subbasin by a weighted average. Subsequently the amount of water, sediment and nutrients that come out from each subbasin enter the respective river.

A modified SCS curve number method is used to calculate the surface runoff for each HRU, based on landuse, soil parameters, and weather conditions. The water is stored in four storage volumes: snow, soil moisture, shallow aquifer and deep aquifer. The processes that are considered within the soil profile are infiltration, evaporation, plant uptake, lateral flow, and percolation. What is important in our study is that melted snow is handled by the model the same way as the water that comes from precipitation regarding the calculation of runoff and percolation. Furthermore, runoff from frozen soil can also be calculated by defining if the temperature in the first soil layer is less than 0ºC. Even though the model still allows significant infiltration when the frozen soils are dry, the runoff of frozen soils is larger than that of other soils. A detailed description of the theory behind the model is described in detail in Arnold et al. (1998) and Srinivasan et al. (1998).

Snow processes in high alpine areas is strongly influenced by the terrain features (Ahl et al., 2008;Zhang et al., 2008). Fontaine et al. (2002) revealed the role of elevation in the spatial and temporal state of the snowpack. Therefore, the definition of elevation bands within the model subbasins can significantly improve the performance of the model in watersheds in high altitudes and large elevation gradients. With the improved snow melting algorithm (Fontaine et al., 2002), the stream flow of alpine regions could be successfully simulated by SWAT (Rahman et al., 2013;Omani et al., 2017;Grusson et al., 2015).

3.2 Input data

The basic input data required by SWAT are: topography, soil, landuse and meteorological data.

3.2.1 Topography

The topography of both study areas was defined using a high precision Digital elevation model (DEM) with a grid cell: 2mx2m (swissALTI3D), produced by the Swiss Federal office for Topography, swisstopo (http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/height/swissALTI3D.html). Following the delineation procedure, Damma watershed was divided into 5 subbasins, while the greater area that feeds the Göscheneralpsee was divided into 25 subbasins. By setting the lowest possible thresholds for landuse, slope and soil, 48 HRUs were created for Damma watershed and 285 HRUs for the greater area. Finally, six elevation bands were defined for each subbasin of both study sites.

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3.2.2 Soil and landuse map

In order to better describe the glacier forefield and to reduce the uncertainty of the calibration for the Damma glacier watershed, we created a more detailed soil and landuse map based on the observations, field and experimental data from the Biglink and SoilTrEC projects (Bernasconi et al., 2011;Dumig et al., 2011;Andrianaki et al., 2017). The soil map was created by adding new soil types to the SWAT database while the land use classes were based on existing types in the database. For the greater area of Göscheneralpsee, we used a soil map, produced by the Swiss Federal Statistical Office at a scale of 1:200,000 (http://www.bfs.admin.ch/bfs/portal/en/index.html). For the landuse, we used the Corine land cover dataset 2006 (version 16, 100m resolution) produced by the European Environmental Agency (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2).

3.2.3 Climate data

Meteorological data from one local weather station and one station of the ANETZ network were used in this study. The weather stations are located at the Damma glacier watershed (2025 m a.s.l.) and at Gütsch (2283 m a.s.l.). The meteorological data of the weather Gütsch were provided by MeteoSwiss. The selection of the weather station Gütsch was based on the results of previous research that showed that it has the best correlation in comparison to other weather stations located in the area (Magnusson et al., 2011) with a long enough record for this study. The data from both stations consist of sub-hourly records of air temperature, precipitation, wind speed, relative humidity, incoming short-wave radiation and incoming long-wave radiation from 2007–2013 for Damma weather station and 1981–2010 for Gütsch. The lapse rates for temperature and precipitation, which are very important parameters in SWAT model since they affect snow and glacier melt, and the interpolation methods were based on the findings of Magnusson et al. (2011) who carried out non-prognostic hydrological simulations for the Damma glacier watershed.

Climate change scenarios -. The climate change predictions were provided by the EU regional climate modelling initiative ENSEMBLES (van der Linden and Mitchell, 2009) and were based on the emission scenario A1B. The model chains produced by the ENSEMBLES project are a combination of a general circulation model (GCM) with a regional climate model (RCM). In Switzerland, model chain data were interpolated to the locations of the MeteoSwiss stations and the Swiss Climate Change Scenarios CH2011 were created (CH2011, 2011). The method used for the creation of the datasets is the “delta-based approach”. For this method the temperature and precipitation predictions are calculated using daily temperature changes (ΔT), and precipitation scaling factors (ΔP). Incoming short-wave irradiation, wind speed and relative humidity were left unchanged. In Switzerland it is predicted that the mean temperature will increase 2.7–4.1°C and the precipitation during the summer months will decrease 18%–24% by the end of the century, in the case when no actions for the mitigation of climate change are taken (CH2011, 2011).

In this study, three climate scenarios with interpolated data for Gütsch weather station are used. These scenarios are: the CNRM ARPEGE ALADIN scenario, the ETHZ HadCM3Q0 CLM scenario, which predicts the highest (ΔT) and (ΔP) in comparison to the other two, and the SHMI BCM RCA scenario, which predicts the lowest (ΔT) and (ΔP), referred to as CNRM, ETHZ and SHMI respectively. Data resulted from the work of (Bosshard et al., 2011). The following periods were selected, in agreement with the duration of the reference period:

Reference period (T0): 1981–2010

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Near future period (T1): 2021–2050
Far future period (T2): 2070–2099

In agreement with the predictions for Switzerland, the scenarios for Gütsch weather station predict warmer and dryer summers and slightly increased precipitation in autumn. The highest ΔT for the near future period is 1.5°C in the mid-summer, 2.5°C in late spring, and below 1.0°C in early summer for the CNRM, ETHZ and SHMI respectively and for the far future period is approximately 5°C in the mid-summer, 4°C along the whole summer and 3°C in early summer respectively. The biggest temperature increase is predicted at the end of the century when the strongest agreement between the different model chains is observed. Precipitation changes for the near future period are within the natural variability apart from a clear trend in dryer summers. The trend of dryer summers is most prominent for the far future period. Furthermore, most model chains predict slightly higher precipitation in autumn. The average ΔP value for the near future period is 1.0 and for the far future period is 0.99. The climate change data were also used in previous study for the same region by Kobierska et al. (2013) and for different sites in the Alps (Bavay et al., 2013;Farinotti et al., 2012a).

3.2.4 Runoff data

Runoff of the Dammarreuss stream that drains the Damma glacier watershed was measured every half an hour at a gaging station at the outlet of the watershed (Magnusson et al., 2011). The runoff of the total area that feeds the Göscheneralpsee is the input of the reservoir and the data from 1997–2010 were provided by the energy company that is responsible for the management of the reservoir.

3.2.5 Glacier extend

Data on the glacier extent for the present period but also for the different climate change scenarios were provided by Paul et al (2007). Paul et al (2007) estimated the evolution of the Swiss glaciers by using hypsographic modelling, based on the shift of the equilibrium line altitude. However, SWAT is not a model that considers glacier flow dynamics and therefore, in this study, the glaciers were incorporated in SWAT as the initial snow content in each subbasin and for each elevation band. The initial snow is given as the equivalent depth of water in mm instead of snow as the density of snow can be variable. For this reason, the calculation of the snow water equivalent was conducted by considering an average density of ice.

3.3 Model calibration

SWAT was calibrated for the Damma watershed only, using the meteorological data from 2009 to 2011 and validated with the data from 2012 to 2013. Data for the years 2007 and 2008 were used for the warm-up and the stability of the model.

The first step of the calibration was the manual calibration. The manual calibration was followed by an automatic calibration and uncertainty analysis using the SWAT-CUP software with the Sequential Uncertainty Fitting ver. 2 (SUFI-2) algorithm for inverse modelling (Abbaspour et al., 2007). Starting with some initial parameter values, SUFI-2 is iterated until (i) the 95% prediction uncertainty (95PPU) between the 2.5th and 97.5th percentiles include more than 90% of the measured data and (ii) the average distance between the 2.5th and 97.5th percentiles

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is smaller than the standard deviation of the measured data. A model is considered calibrated when R^2 or other chosen criteria between the best simulation and calibration data reaches the best value (Abbaspour et al., 2007).

The criteria used are the Nash-Sutcliffe (Nash and Sutcliffe, 1970) model efficiency (NS) and the square of Pearson's product moment correlation is indicated with R^2. The NS shows the relationship between the measured and the simulated runoff (Eq. 1). R^2 (Eq. 2) represents the proportions of total variance of measured data that can be explained by simulated data. Better model performance is considered when both criteria are close to 1. NS coefficients greater than 0.75 are considered ''good,'' whereas values between 0.75 and 0.36 as ''satisfactory'' (Wang and Melesse, 2006).

$$NS = 1 - \frac{\Sigma(y-\hat{y})^2}{\Sigma(y-\bar{y})^2}, \quad (1)$$

$$R^2 = \left[\frac{\Sigma(y-\bar{y})(\hat{y}-\bar{y})}{\sqrt{\Sigma(y-\bar{y})^2}\sqrt{\Sigma(\hat{y}-\bar{y})^2}}\right]^2, \quad (2)$$

Where y is the individual measured value, $\hat{y}$ for the individual simulated value and $\bar{y}$ the mean measured value.

After calibration, we applied SWAT for the greater area that feeds the Göscheneralpsee, using the parameters that resulted from the calibration of the model for Damma watershed. This means that in this case SWAT was set up using the input data (DEM, soil, landuse and meteorological data) described above but was not recalibrated. The parameters were adjusted according to the calibration of Damma watershed. Results of the model were then compared to data of the input of the Göscheneralpsee reservoir that were provided by the energy company that manages the reservoir. We consider that this is a validation step that helps to assess the performance of the model for an area with similar characteristics to that of the Damma watershed. This approach can prove to be useful in cases where there is scarcity in meteorological data or upscaling of the model is needed.

4 Results and Discussion

4.1 Model Calibration

The most sensitive parameters during manual calibration are the ones related to snow melt such as: i) TIMP, which is the parameter for the snow pack temperature lag factor, ii) SMFMX, the snow melt factor on the 21st of June (mmH2O / ºC-day), iii) SMFMN, the snow melt factor on the 21st of December (mmH2O / ºC-day), CN_FROZ, which was set to active in order for the model to consider the frozen soil and finally the snow fall and snow melt temperature SFTMP and SMTMP respectively. Groundwater flow parameters such as the GW_DELAY, the groundwater delay time, ALPHA_BF, the base flow alpha factor and the SURLAG, the surface runoff lag coefficient, were also found to be sensitive.

TIMP was set to a very low value indicating that the glacier is not affected by the temperature of the previous day as much as the snowpack would be. Snow and glacier melt in Damma watershed occurs from April to September a fact that explains the low value of the SMFMN parameter (0.1 mmH_2O / ºC-day), the minimum melt factor, while the SMFMX is set to the value of 4.7 mmH_2O / ºC-day. SURLAG and GW_DELAY play an important role

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in the model performance as they control the melted snow routing process and the hydrologic response of the watershed. Damma glacier watershed has a fast response and therefore SURLAG was set to the very low value of 0.001 while GW_DELAY to 0.5 days. SMTMP is also sensitive since it is the controlling factor for the initialisation of the snow melt, considering the availability of snow for melting on a specific day. As a result, model-generated peak runoff is significantly influenced by the variation in SMTMP. Finally, ALPHA_BF was set to value 0.95, which is a typical value for a fast response watershed.

The automatic global sensitivity analysis was conducted with SWAT-CUP software and 17 input parameters were analysed and are presented in Table 1. It revealed that the most sensitive parameters are the same as the ones observed during manual calibration. More specific the most sensitive ones in descending order are TIMP, GW_DELAY, SMTMP, SMFMX, ALPHA_BF and SURLAG with p values 0 for TIMP and very close to 0 for the remaining parameters. The least sensitive parameters were left to their default value.

A comparison of the results of the model using the default model parameters and the observed values is presented in Fig. 3(a), while the results of the calibrated model in comparison to the observed values are presented in Fig. 3(b). The hydrograph produced by the uncalibrated shows that runoff is significantly overestimated due to excessive snow and glacier melt produced by the default parameters. Calibration improved considerably the fit of the model to the observed data and the results of the calibrated model matched the observed data throughout most of the year. The best fit was observed in April until June, when runoff is dominated by snowmelt. The graph of the accumulative runoff (Fig. 3(c)) shows that runoff is slightly overestimated in July and August, when it is dominated by glacier melt. Best results occur for the years 2009 and 2010. 2011 is characterised by unusually dry September, October and November which resulted in low performance for the respective months and underestimation of the runoff. Even so, model performance for the calibration period was very good, with Nash-Sutcliffe efficiency of 0.84 and R^2 of 0.85 for daily runoff predictions.

4.2 Model Validation

The model was validated using two different approaches. For the first approach, we validated the model, using the meteorological data for 2012 and 2013 and results are presented in Fig. 4(a). The accumulative graph in Fig. 4(b) reveals that there is the same trend in the validation period as the one observed in the calibration period, with best fit during spring and early summer while in July and August the estimated runoff is slightly lower. A small exemption to that is in late spring of 2012, when estimated runoff is underestimated, probably due to the extremely wet May in that year that cannot be efficiently simulated. Overall, model performance during validation is very satisfactory and almost identical to that of calibration, with Nash-Sutcliffe efficiency of 0.85 and R^2 of 0.86. Therefore, the model is considered to be validated. The small seasonal differences in model performance are due to the fact that runoff in spring and early summer, that is from May till June, originates mainly from snowmelt while in July and August originates from glacier melt. Although there are two different water sources during the two different periods, we can only assign one set of parameters. Nevertheless, differences are very small and therefore, it is confirmed that SWAT can be successfully applied for a partly glacierised watershed.

The results of the model for the greater area that feeds the Göscheneralpsee, are presented in Fig. 5(a). Model performance criteria were lower in this validation step compared to the calibration period, but still indicated

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satisfactory results. The efficiency of inflow predictions (NS) dropped to 0.49 and the R^2 to 0.72, which are however satisfactory. The observed and predictive accumulative flow is presented in Fig. 5(b).

This successful validation approach shows that the model can be applied, without recalibration, for a greater area with similar climatic conditions. This methodology can be an ideal way of model validation in studies that include climate change scenarios, since it helps in assessing the uncertainties that occur due to climate change or evolution of land use. It can also be useful in cases where there is scarcity of runoff data but good quality of GIS input data. In conclusion, this was an exercise of upscaling the model and it can be used in numerous other studies.

Finally, SWAT results were compared with results from PREVAH and ALPINE3D models for the greater area that feeds the Göscheneralpsee, already published in Magnusson et al. (2011) and Kobierska et al. (2013) (Fig. 6). PREVAH is a semi-distributed conceptual hydrological model suited for applications in mountainous regions (Viviroli et al., 2009a;Viviroli et al., 2009b) while ALPINE3D is a fully-distributed energy-balance model (Lehning et al., 2006). Both models performed very well, with NS efficiencies of 0.85 and 0.91 for ALPINE3D and PREVAH respectively.

Figure 6 shows the average of the period 1981-2010 daily runoff for each model. It is observed that SWAT overestimated the runoff of the snowmelt period, in May and June, while for the rest of the season its results are close to the observed values and in agreement with the other two models. Considering the fact that SWAT was applied for the Göscheneralpsee and for 30 years without further calibration, its results are considered very satisfactory. Its performance is comparable to that of PREVAH and ALPINE3D, however its advantage over the other two models is that is a model widely used around the globe for different areas and projects, with easily available input data. This makes it an ideal choice for water managers and policy makers. ALPINE3D and PREVAH models have been used mainly in mountainous areas and have high requirements in meteorological data and computational time.

4.3 Results from climate change simulations

The climate change scenarios were run for the greater area that feeds the Göscheneralpsee. The following periods were selected, in agreement with the duration of the reference period:

Reference period (T0): 1981–2010
Near future period (T1): 2021–2050
Far future period (T2): 2070–2099

The results of SWAT model are presented as the average runoff for each different scenario along the whole period in Fig. 7(a) for the near and in Fig. 7(b) for the far future periods. The results show many similarities regarding the seasonality of runoff for the three different scenarios for all the simulation periods.

During the reference period, which describes the current situation, runoff peaks in early July when snowmelt is combined with glacier melt. For the near future period T1, the main difference is noted from July to September when runoff is dominated by glacier melt. During this period, predicted runoff for all scenarios, and in particular for the warmer ETHZ scenario, is lower than the reference period, indicating that the glacier melt cannot

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compensate the decrease in the precipitation, estimated by the future climatic data. From September until the end of the season, simulated stream flow of all scenarios is higher than the one of the reference period, which is explained by the higher predicted precipitation during autumn. Moreover, the predicted prolonged warm period leads to increased glacier melt and therefore higher runoff. The annual peak continues to be observed in early July, since the glacier hasn't melted away yet providing a significant source of water through glacier melt.

For the far future period T2, runoff from spring to mid-June is predicted to be significantly higher for all three scenarios than that of the reference period. This can be explained by considering that the warming climate leads to faster rates of snow melt and increased runoff in snowmelt dominated period. In addition, higher precipitation is predicted by the climatic data for this period. In 2070 the total volume of the Damma glacier is estimated to be reduced to almost half, resulting in significant drop of the volume of water that comes from glacier melt between July and late August. For this reason, and in combination with the significant decrease in precipitation predicted by all scenarios for this period, the simulated runoff is lower than that of the reference. Finally, the snow free period of the watershed is prolonged until December instead of September.

At the end of the far future period, the average temperature increase in our site will be 3.35ºC and only a small part of the Damma glacier will be left in high elevation. The peak of the highest runoff is significantly shifted and is projected to be in the beginning of June. The main volume of runoff is expected to be observed in spring and early summer while during the glacier melt period, streamflow is significantly lower than that of the reference period. Overall the total water yield for the far future scenario is significantly decreased. These findings are of great significance for water resources management.

In order to better observe the seasonal changes of estimated runoff, Fig. 8 shows the average runoff for a) May-June, b) July-August and c) September-October for the T1 and T2 future periods divided by the average of the reference period of the same months for all the three scenarios. In May and June, as mentioned above, runoff is mainly dominated by snowmelt. The three climate change scenarios predict increased temperatures and higher precipitation during May and June which result in faster snowmelt and therefore in the increased predicted runoff, as observed in Fig. 8(a). The increase is higher in the far future period due to the higher temperatures. The only exemption to that is the SHMI scenario for the near future period, since it is the colder scenario that predicts the lowest temperature and precipitation changes. In July and August climate scenarios predict a significant decrease in precipitation, which is also depicted in the predicted runoff. As seen in Fig. 8(b), predicted to reference runoff ratio is considerably below one, especially in the far future period. The scenario that has the most drastic effect is the ETHZ because it is the warmer scenario that predicts the highest increase in the temperature and decrease in the precipitation. Finally, for September and October, results do not show a clear trend for the warmer ETHZ scenario, however for the CNRM and SHMI scenarios, future runoff is lower than the reference. The big shifts in the ratio especially in the far future period T2 can indicate the increase in extreme events.

The variability between the predictions of the three scenarios can be explained by the difference in the projection of temperature and precipitation. The variability between the scenarios can be a measure of the magnitude of the uncertainties associated with climate modelling (Kobierska et al., 2013).

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5 Conclusions

This study showed that SWAT can be used efficiently for the hydrological modelling of the Damma glacier watershed CZO and for the assessment of the effect of climate change on future runoff. The efficiency of the model in this high alpine and partly glacierised watershed is comparable to that of models traditionally used to high mountainous areas such as ALPINE3D and PREVAH.

One of the novelties of this study is that the model was validated by applying the calibrated version of the model for a greater area that included Damma glacier watershed and for a longer meteorological record. The performance of the model for this validation step was satisfactory. This approach helped us to assess the uncertainties related to the hydrological model and to show that the model can perform well for an area with similar but not identical land use and climate forcing. This conclusion was extremely valuable for the subsequent analysis of the impact of climate change on the hydrology of the watershed. Furthermore, this methodology of upscaling SWAT can have various other uses.

Climate change predictions showed that daily and total annual runoff will change significantly in the future especially towards the end of the century. Daily runoff during spring and early summer, in May and June, is predicted to increase because of faster snow melt and the predicted wetter springs. Projected runoff from July to October for the far future period, when the major part of Damma glacier will have already disappeared, but also for the near future, is significantly decreased. These results proved that SWAT shows sensitivity for the modelling of glacier melt, which is crucial for the climate change assessment and therefore can be a useful tool for water managers and policy makers.

Author Contributions

Maria Andrianaki applied SWAT model, analysed data and prepared the manuscript with contributions from all co-authors. Juna Shrestha reviewed the manuscript and assisted in the modelling procedure. Florian Kobierska provided meteorological and runoff data. Nikolaos P. Nikolaidis provided guidance for the research goals. Stefano M. Bernasconi was the supervisor of the research project and provided the funding that lead to this publication.

Competing interests

The authors declare that they have no conflict of interest.

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Parameter	**Unit**	**Cal. Value**	**Default**
SFTMP	ºC	-0.5	1
SMTMP	ºC	2.5	0.5
SMFMX	mmH_2O / ºC-day	4.7	4.5
SMFMN	mmH_2O / ºC-day	0.1	4.5
TIMP		0.011	1
SURLAG		0.001	4
CNCOEF		0.5	1
SNOCOVMX	mm H_2O	500	1
SNO50COV	%	0.3	0.5
ALPHA_BF	days	0.95	0.048
GW_DELAY		0.5	31
GW_REVAP		0.02	0.02

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LAT_TTIME		0.0001	0
CN2		35	Na
SLSOIL	m	5	Na
ESCO		1	0.95
SOL_AWC	mm H_2O/mm soil	0.05	Na

Table 1: The default and calibrated values of the most sensitive during calibration SWAT parameters

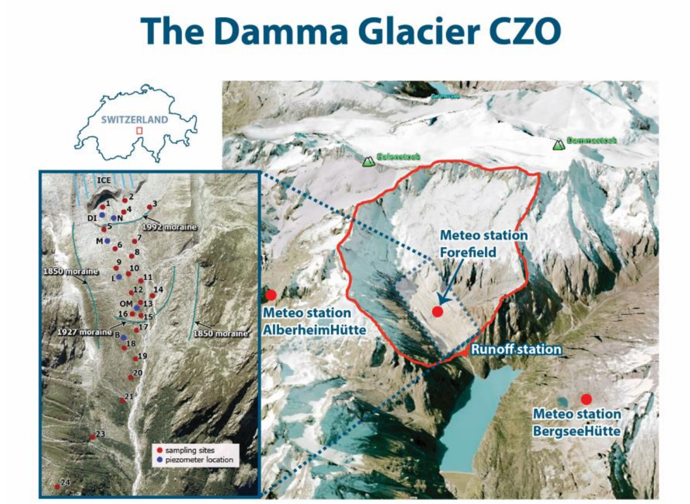

Figure 1: Map showing the Damma glacier CZO. The watershed of the Damma glacier is depicted by the red line.

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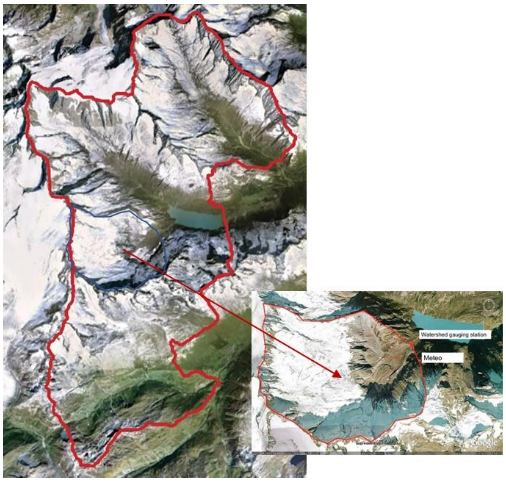

Figure 2: Map showing the study area that feeds the Göscheneralpsee and is depicted by the red line. Damma watershed is in the middle of the area and is shown with a blue line.

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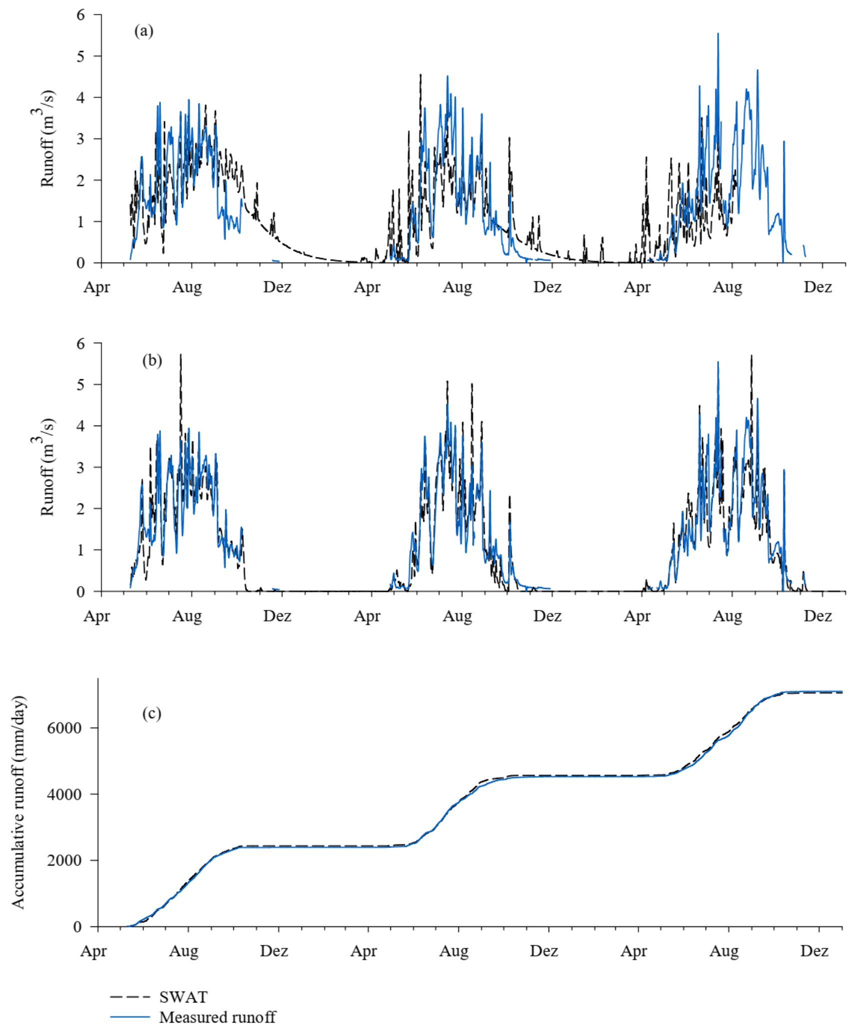

Figure 3: Results from the calibration of SWAT model in comparison to the measured runoff of Damma watershed (a) before the calibration of the model and (b) after calibration. Graph (c) shows the simulated (after calibration) and measured accumulative runoff over the calibration period.

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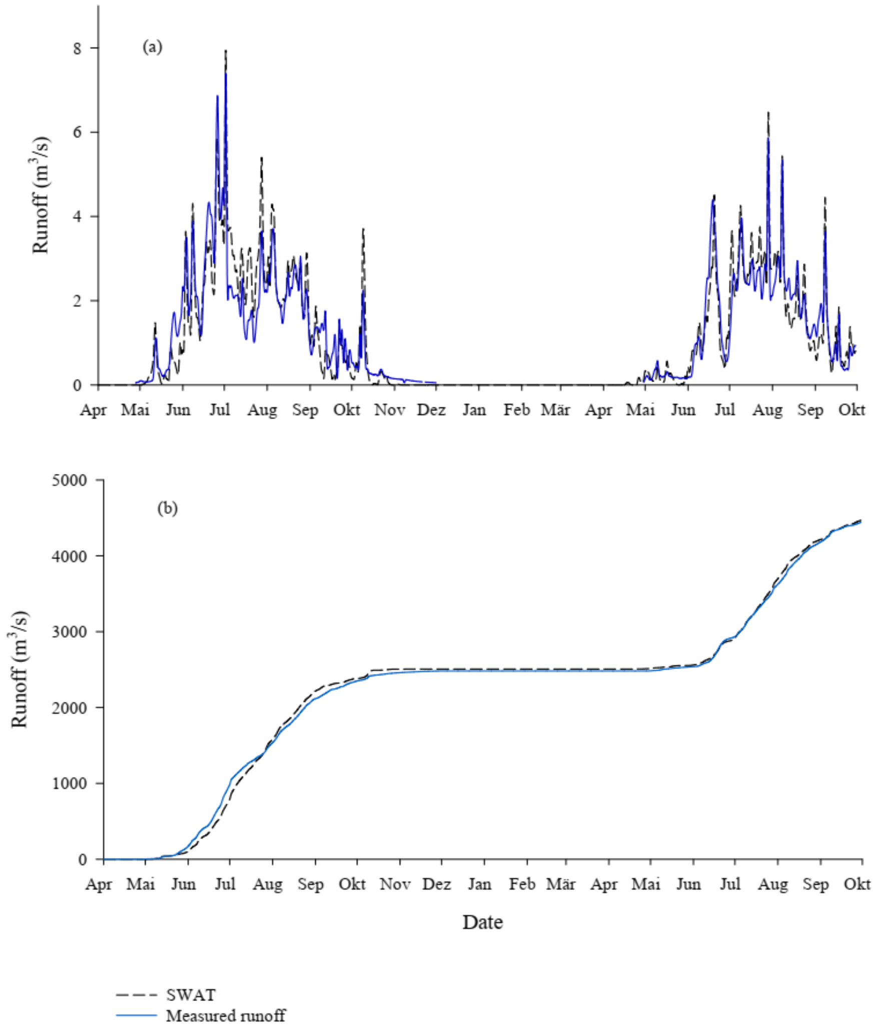

505

506 **Figure 4: Results of the SWAT model compared to the measured runoff of the Damma watershed for the validation**
507 **period. Graphs in (b) show the accumulative runoff.**

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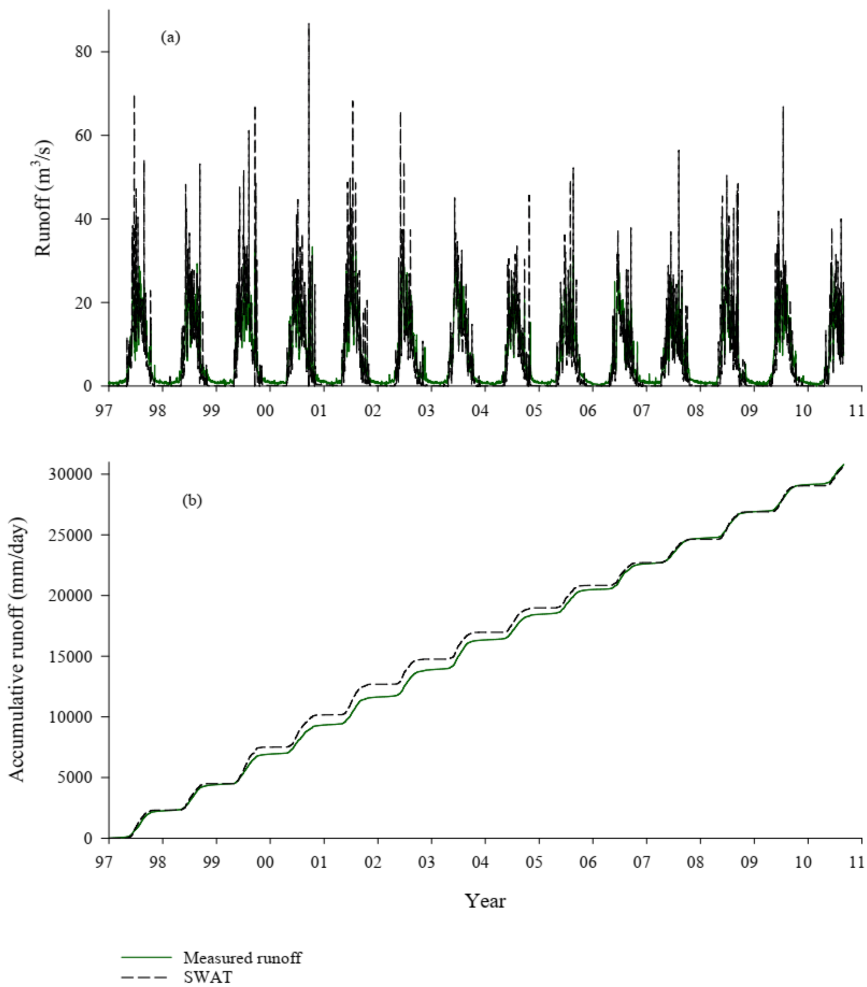

Figure 5: SWAT results and measured runoff values of the feeding catchment of the Göscheneralpsee for the period 1997-2010. Graphs in (b) show the accumulative runoff over this period.

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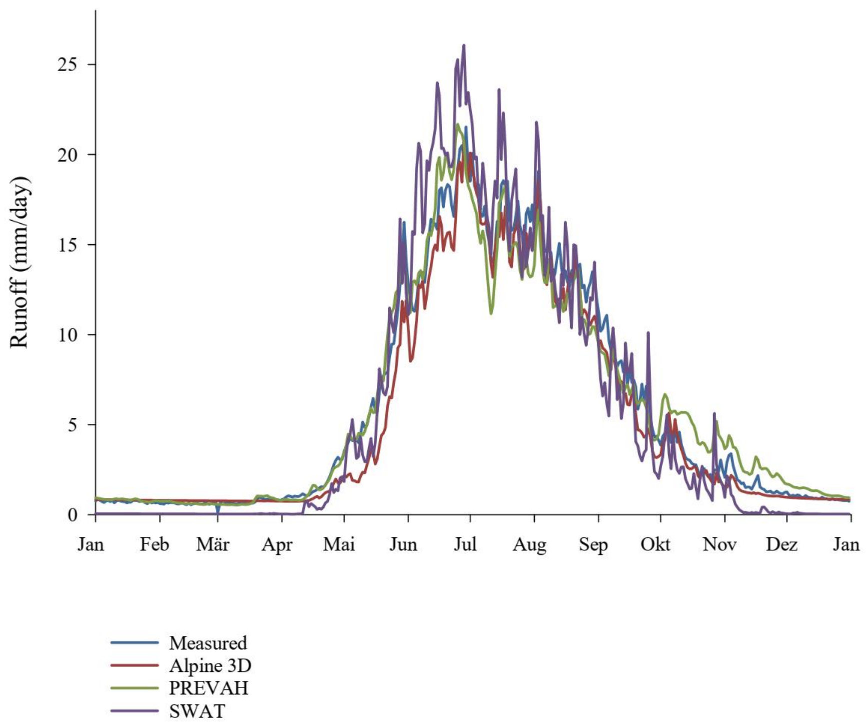

Figure 6: Comparison of SWAT with Alpine3D and PREVAH models and the measured runoff of the Göscheneralpsee feeding catchment for the 1997-2010 period.

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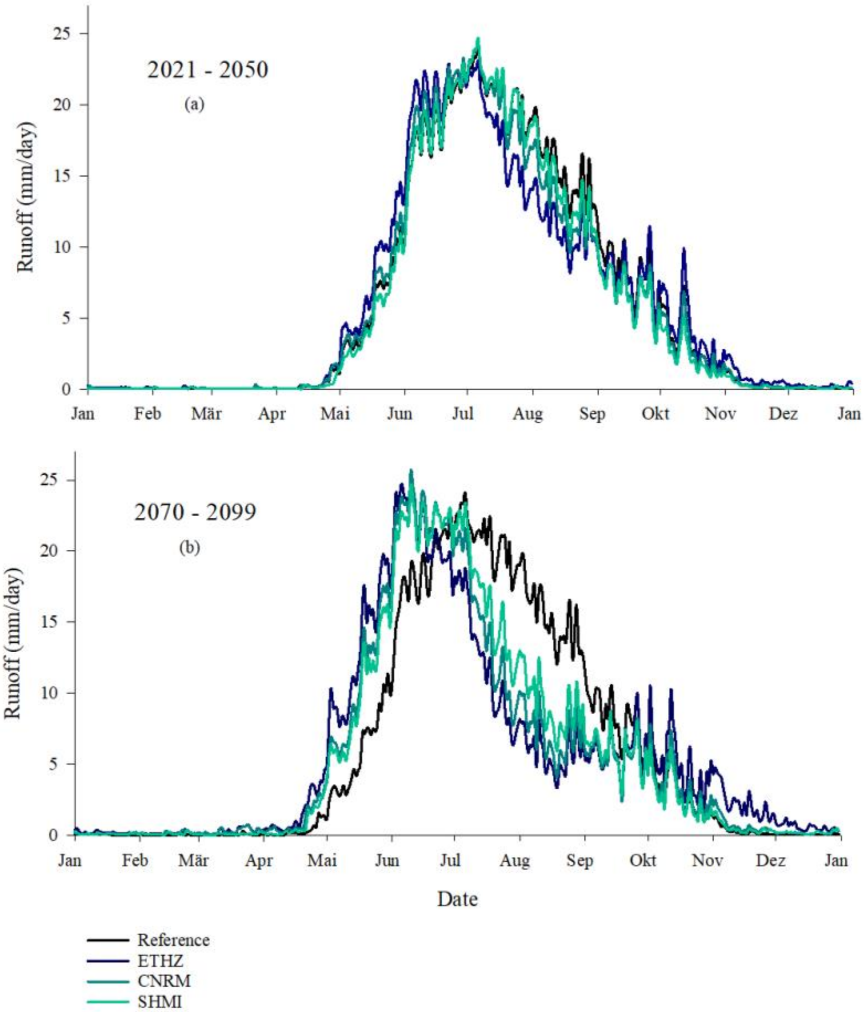

Figure 7: SWAT results of the three future scenarios for the reference and both future periods.

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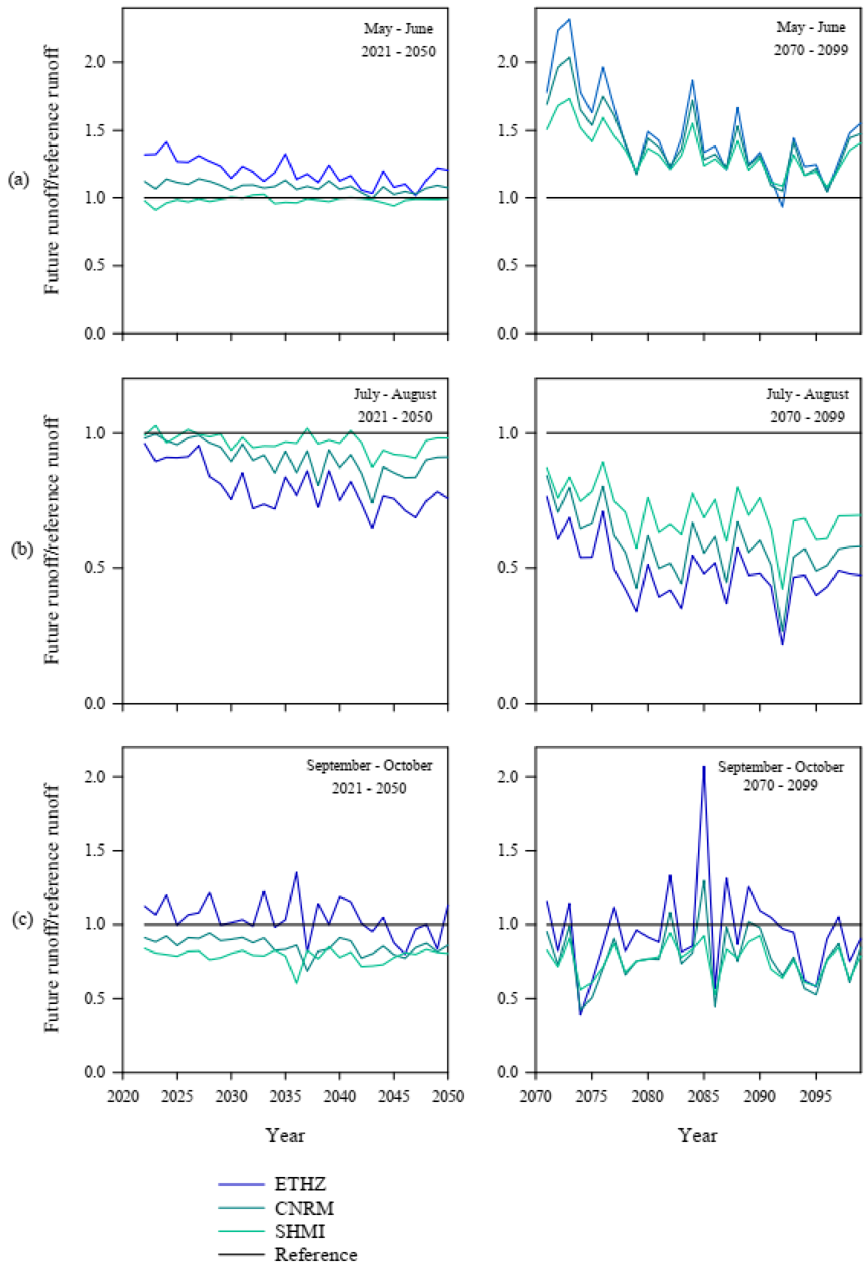

Figure 8: Seasonal changes of future runoff for the reference and future periods for all the three future scenarios.