Dear Editor,

We would like to thank you and the reviewers for your very constructive comments, that led to a significant improvement of this manuscript. Here we discuss the revisions that we made in response to your reviews and we hope that we addressed all the comments and issues raised by the reviewers.

Firstly, in response to the comment from reviewer 1, G. Thirel, that the title is not very fitting, we suggest a change in the title, if this is possible. The suggested new title is: "Assessment of SWAT spatial and temporal transferability for high altitude glacierised catchments". In addition, we updated in the manuscript one of the coauthors` affiliation. The structure of the manuscript was modified in order to address the main issue raised by the reviewers and concerns the goal of this study and to clarify methodological choices. Two new sections were added; one called Methodology and the second Model setup, calibration and validation. The abstract, introduction and conclusions were completely revised as well as other sections of the text. Figures 1 and 2 as well as 3 and 4 were combined in two new ones, that better describe the study site and the calibration data. A Table was also added with the new analysis data.

Below you will find our answers to the reviewers. A manuscript with all the changes is submitted together with this letter. Please note that the line and Figures numbers have been modified and that we refer to the new numbers in the responses below.

Yours sincerely

Maria Andrianaki (on behalf of all authors)

Dear Reviewer G. Thirel, thank you for your review and constructive comments. I hope that we answer all your remarks.

Reviewer: "The paper by Andrianaki et al. deals with a topic of interest for HESS readers: the modelling of runoff in a glacierised catchments and projections of its evolution. The manuscript reads easily and is concise; I would like to thank the authors for that, as it is often not the case and readers are burdened with loads of not so useful information in many papers.
That said, I feel that there is room for improvement before the paper reads as a scientific paper. Here are my **main remarks**.
1) The main criticism is that I failed to identify clearly what the readers could bring home from this manuscript. Definitely not a new methodology, as the SWAT model is basically used as is, the sensitivity test is not detailed and the calibration and climate change exercises are classical. In my opinion, results are also not so remarkable. It is very interesting to see the validation exercise on a different period and then on a different catchment, but in the end we have results about one catchment and the calibration period is very short. As aconsequence, we could wonder if we have the right answer for the right reason or not. I find it very difficult to extrapolate anything from results on this catchment for further works.
If the main additional value of the paper is the fact that SWAT works for this area, then this should be better highlighted and put into perspective with relevant literature. This reflects on the objectives of the study, which are barely presented in the paper and makes it look like an application of the model rather than an actual research work. Only lines 51-52 give some elements on the interest of this work. Consistently, the conclusions only briefly highlight one novelty of the study (L. 354). In my opinion, the abstract, the introduction and the conclusions should be clear about the novelty of this work."

Authors: You are right that probably we didn't explain clearly enough the objectives of this study.

One of the challenges that researchers in hydrological modelling face is the lack of data for model setup and calibration in ungauged watersheds. Especially in high mountainous regions a big part of the watersheds is ungauged. In the last years, there is an increasing interest in applying SWAT on snow-dominated (Grousson et al., 2015) and glacierised watersheds (Omani et al., 2017; Rahman et al., 2013). However, its transponsability and its application for the simulation of runoff in high altitude ungauged watersheds hasn't been tested yet.

Our study area is characterised by extreme climatic conditions, high altitude and steep slopes. Here, we have a quite unique situation; a small well gauged watershed monitored through the CZO projects, which is part of a larger watershed, for which we have hydrological data thanks to its use by the hydroelectric power plant. This gives us the opportunity to verify the applicability of SWAT under extreme conditions and its transferability on spatial and temporal scale, by using the small Damma watershed (10.5 km^2) as the gauged watershed and the greater area feeding the Göscheneralpsee reservoir (100 km^2) as an ungauged catchment. We used the approach of spatial proximity and transferred the calibrated parameters of the model from the donor watershed, which in this case is the Damma glacier watershed, to the greater area. By comparing the model results with the existing measurements provided by the managers of the reservoir, we were able to test whether the model can eventually be transposed and applied efficiently on a different spatial scale, and where its advantages and disadvantages lie.

Finally, we conducted the climate change simulations, not to do another set of classical climate change exercises, but to investigate whether SWAT can be further transposed on a temporal scale, since we could compare our findings with those of a previous study for the same area, which used two other hydrological models with different characteristics, PREVAH and Alpine 3D (Kobierska et al., 2013).

In addition, the Damma Glacier watershed is a Critical Zone Observatory part of the Critical Zone Exploration Network, a global network of field sites investigating the physical, chemical and biological processes of the critical zone (www.czen.org). Because CZOs are well studied sites and usually have long records of data, we wanted to show how they can be used in water management, since they could serve as parameter donor catchments.

Our results presented in the manuscript, as well as further analysis suggested by the Editor (please see our response to the Editor), showed that SWAT can predict satisfactorily runoff after being upscaled and applied in different scales, even under alpine conditions. This approach, which doesn't require complex regionalisation methods, can be quite useful in water management and climate change studies, considering the fact that SWAT is a widely used model, even in large scale simulations (Pagliero et al, 2014). The performance of the model could be further improved if different rates of glacier melt and snowmelt had been applied.

In the revised manuscript we have rewritten a big part of the abstract and introduction, adding relevant literature, discussing all the above with more detail and explaining the objectives in a clear way. In the conclusions paragraph we discussed in a more critical and constructive way about the performance of the model and how it could be improved and the conclusions from the comparison between the models and the climate change study.

Reviewer:"2) It is, if I'm not wrong, never clearly stated that calibration of SWAT is done compared todischarge observations only. Calibration is mentioned many times (abstract, end of introduction, section 3.3) but the used observation is not given. SWAT is physically based and snow observations are definitely an additional value to models calibration in snowy areas, so it is legitimate to wonder if the authors used any kind of snow data here."

Authors: The model was calibrated against measured runoff of the Damma watershed, which is described in paragraph 3.2.4. Comparison of the measured runoff with the results of the model after the calibration is given in Fig. 2 (former Fig.3), page 19. Small corrections were made in the text to make this clearer.

Data for the evolution of the glacier were available for the whole area (paragraph 3.2.5) provided by Paul et al., 2007 and snow density and snow depth measurements were available for the Damma watershed only. We used the evolution of the glacier to define the initial glacier storage for each elevation band of each subbasin. We didn't use it for the calibration of the model because we wanted to test the performance of the model following a simpler approach that would be familiar to the majority of SWAT users and that would also relate to studies with data scarcity where snow measurements are not available. We also think that the best way to improve SWAT performance in this case would be to take into account the difference between snowmelt and glacier melt dynamics. Omani et al. (2017) addressed this issue by applying different snow parameters to the completely glacierised subbasins. However, the subbasins of the Damma glacier watershed were all partly glacierised so we couldn't follow this approach.

Reviewer: "3) The calibration set up is unclear and at some point, flawed to me. First, we don't know exactly what the objective function is: authors introduce NS and R^2 but they don't specify how they used them: through a composite criterion? With a Pareto front? Then, the use of NS in snowfed basins is not advised. Indeed, this criterion relates the performance to the mean observed discharge, which is a bad predictor in such a seasonally variable environment (see Schaefli and Gupta (2007)). It also underestimates discharge variability.
Finally, we don't know how the parameters from the small basin are transferred to the larger one. Are some of these parameters time or scale dependent? It is just said that they are adjusted.
4) The structure of section 4.1 is not easy to follow. Some kind of sensitivity test is done to identify which parameters to calibrate. I failed to understand if it was done by the authors, and if yes I don't understand why it is mentioned only in the third paragraph, so after talking about the values of the calibrated parameters. Also, the word "set" is often used to refer to parameters; as it is unclear what is meant since both a manual calibration and an automatic one are mentioned, I got a bit lost.
In addition, authors seem to infer that Table 1 shows the results of a sensitivity test. What I rather see here is how different the calibrated values are from the default ones, some of them being unrealistic maybe (I don't know where they come from). L. 239: which ones are the least sensitive ones?"

Authors: Initially we conducted the calibration manually because we wanted to identify the parameters that really influence the hydrology of the site. For the manual calibration both NS and R^2 were checked but again manually. After the manual calibration we used SWAT-CUP software and the program SUFI-2 (Sequential Uncertainty Fitting version 2) (Abbaspour et al., 2007) for the automated calibration (fine tuning) and the sensitivity analysis. The manual calibration helped us in defining which parameters will be calibrated by SUFI-2 as well as their range. For example, because our site is above the tree line,evapotranspiration is not significant, and ET related parameters were left to their default values. For the SUFI-2 NS objective function was chosen because it was the criterion available in SUFI-2, which is most commonly used in similar studies.

Table 1 doesn't show the sensitivity test. It shows the default and calibrated values of the parameters that were introduced into SUFI2 and were calibrated. The sensitivity test showed that these parameters are indeed the most sensitive ones. Some of these values are very different from the default ones probably because our watershed is characterised by extreme conditions. For example, due to its topography (very steep slopes) and geology Damma watershed has a very fast response which led to the high value of ALPHA_BF and the low value of GW_DELAY.

The input data of SWAT include topography, landuse and soil maps and during the initial delineation of the watershed many parameters are given a value based on these data. This a priori parameterisation assisted the use of the model for the bigger area. Then the calibrated parameters were applied to the bigger area with the same values that resulted from the calibration without any regionalisation procedure or another adjustment. We decided to do that because the Damma watershed and the greater area are very similar.

After receiving your review, we calculated the Benchmark Efficiency according to Schaefli and Gupta (2007) and for the period 2009-2011 the BE value is 0.22 and for 2012-2015 the BE is 0.25. The calculation of BE is included now in the revised text. Furthermore, more detail was added in the calibration paragraph to make it better understood. The calibration, criteria, sensitivity analysis and results are presented altogether in section 5.

Reviewer:"5) The actual setup of this whole study is not justified by the authors. Why is the modelcalibrated on the small basin that has few data and validated on the large basin with a lot ofdata rather than the opposite?"

Authors: As mentioned above, in this study we have a quite unique situation; a small well gauged watershed monitored through the CZO projects, which is part of a larger watershed, for which we have hydrological data thanks to its use by the hydroelectric power plant. This way we wanted to check the application of SWAT in high altitude basins and its upscaling to ungauged catchments in alpine conditions. Since we already had the climate change study with Alpine 3D and PREVAH for the bigger area, we calibrated the model for the small watershed and transferred it to the bigger. In the revised text we explain this further by adding more detail in the Abstract, Introduction and conclusion as well as in the added section 4 Methodology.

Reviewer: "6) L. 304: I thought that the black (reference) curve in Fig. 7 should be the same as the SWATcurve in Fig. 6, but it does not seem so. Did I get something wrong? The resolution of Fig. 7could be improved, it is more difficult to read than Fig. 6."

Authors: You are right. There is an error in the text, (former line 284) now in line 366. In Figure 4 (former Fig. 6) the interannual average is for the period 1997-2010 and not 1981–2010 mentioned in the text. The caption of Fig.6 is correct. In Fig. 5 (former Fig.7) the reference period is 1981-2010. Former Figures 6 and Figures 7 were redone and are now Fig. 4 and 5.

Reviewer: "7) L. 317: the authors state that the volume of the glacier reduces to half in 2070. I wonder how this is considered in the SWAT model. Indeed, I expect that the initialconditions of the model (due to the Delta method used for producing the climate projections a continuoushydrological projection cannot be done) had to be adjusted. How was that done? Also,please precise who estimated this reduction (authors? Literature?)."

Authors: Line 402 – 403. We have data for the evolution of the glacier for both future periods provided by Paul et al. (2007). Based on this, the initial glacier storage was calculated, and the SWAT was setup for each climate change scenario. According to the data of the evolution of the glaciers the glacier volume will be reduced in our site approximately to half by 2070. The sentence was rephrased to explain this better.

Minor remarks:

Reviewer: "Title: The title is not very sexy… Also CZO is an acronym, is it well known enough to be used in a title?"
Authors: Indeed, the title is not very sexy. We suggest another title could be "Assessment of SWAT spatial and temporal transferability for high altitude glacierised catchments". CZO is removed from the title.

Reviewer:"L. 30, 32 and many other places: a space is missing after the semi-colon."
Authors: Corrected

Reviewer: "L. 31: I think that the lack of observed data of sufficient quality could also be mentioned."
Authors: Done. Currently L. 38

Reviewer: "Section 2: what is the surface area of the small watershed? It is only given for the larger one."
Authors: The area of the small watershed is 10.5 km^2. Now it is added in the text. L. 75

Reviewer: "L. 60: after "(Fig. 1)" I think that "is" is missing."
Authors: Done, Figure 1 was merged with Figure 2

Reviewer: "L. 62: inconsistent (lack of) space between number and unit."
Authors: Corrected

Reviewer:"L. 69, 74…: why is "et al." suddenly in italics?"
Authors: Corrected

Reviewer: "L. 77: I would add a comma after "interface""
Authors: Corrected

Reviewer:"L. 135: strange punctuation after "Climate change scenarios"
Authors: Corrected, L.150

Reviewer: L. 149-150: are the parentheses necessary around Delta P and Delta T? "(Bosshard et al. 2011)" should be "Bosshard et al. (2011)"
Authors: Corrected, L. 155

Reviewer:L. 158: I would add "scenarios" after "SMHI"
Authors: Added, L. 165

Reviewer:L. 164: if I got it right, Delta P close to 1 mean no change. Is it correct?
Authors: Yes

Reviewer:L. 172: “extenT”
Authors: Corrected, L. 187

Reviewer: L. 211: what you have done is a proxy-basin sample test according to the well-known paper Klemes (1986). This is not done so often, I recommend citing this paper
Authors: You are right that our approach is similar to the proxy basin sample test suggested by Klemes (1986) and we added this paper in the introduction together with a short description of the test in section 4.

Reviewer:L. 220: “temperatureS”
Authors: Corrected, L. 241

Reviewer:L. 225: I would add a comma after “September”
Authors: Corrected

Reviewer:L. 302: I also see a shift of the peak for the far future
Authors: The sentence in L.302 was deleted because it was not clear enough.

Reviewer:L. 320: “snow-fre”
Authors: Corrected

Reviewer:L. 323: using the future is a bit too categorical. There are some uncertainties in projections.
Authors: Some sentences were rephrased to emphasize that these are predictions. L.382 - 435

Reviewer:L. 360: any ideas about these other uses? I think this is of interest for the readers.
Authors: This approach could be used in the simulation of runoff in high altitude ungauged catchments with limited data or in large scale simulations with SWAT. Big part of the conclusions, now section 7, was rephrased to explain this in a better way.

Reviewer: L. 428: Farinotti et al. (2012) is given twice. L. 471: Viviroli et al. (2004) has been published, please update L. 480: “SIMULATION1”: what is this “1”?
Authors: Errors in the references were corrected

Reviewer: Table 1: space or no space between “mm” and “H2O”? In the caption, I would place “SWAT parameters” just after “sensitive”
Authors: Corrected

Reviewer: Fig. 1 and 2: scale and north direction are missing. I would skip “The Damma Glacier CZO” on top of Fig. 1.

Authors: Figures 1 and 2 were combined in one. L. 644

Reviewer: Fig. 3 and others: months are not given in English ("Dez"). I would also lie to see each time in the caption the catchment of interest and the period.
Authors: Former Figures 3 and 4 were combined in 1 and is now Figure 2. Sorry for not noticing about the months that are not in English. It is corrected. The captions were corrected to include catchment and period. The graph with the results from the default parameters was deleted

Reviewer: Fig. 5: panel (a) is too small for the long period given; it hides potential serious mismatches between simulation and observations.
Authors: Figure 3 (former Fig. 5) We tried to apply a different colour scheme and it is slightly improved.

Reviewer: Fig. 6: is it 1981 as in the text or 1987? Is that an interannual mean? Please comment why SWAT underestimates low flows.
Authors: Figure 4 (former Fig. 6) The caption is correct. The 1981 in the text was wrong but now is corrected. It is true that SWAT underestimates low flows and this discussion is added in the revised manuscript L. 344 - 359. The Damma glacier watershed is characterised by very steep slopes (even up to nearly 80 degrees) and runoff originates mainly from snowmelt, glacier melt and rainfall (Magnuson et al., 2012). Consequently, the watershed is characterised by very fast response, which in terms of the model parameters resulted on the high value of ALPHA_BF and the low value of the GW_Delay. On the other hand, the Göscheneralpsee feeding area is less steep on average and maybe the interactions between groundwater and surface runoff must be more significant than those of the Damma watershed. Furthermore, two out of the four watersheds of the greater area are drained into the reservoir through tunnels, which undoubtably influence the low flow measurements of the reservoir. These factors explain why the model, which is calibrated for the Damma watershed, doesn't simulate successfully the low flows of the greater area.

References

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., and Srinivasan, R.: Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT, J. Hydrol., 333, 413-430, http://dx.doi.org/10.1016/j.jhydrol.2006.09.014, 2007.

Grusson, Y., Sun, X., Gascoin, S., Sauvage, S., Raghavan, S., Anctil, F., and Sáchez-Pérez, J.-M.: Assessing the capability of the SWAT model to simulate snow, snow melt and streamflow dynamics over an alpine watershed, J. Hydrol., 531, 574-588, http://dx.doi.org/10.1016/j.jhydrol.2015.10.070, 2015.

Omani, N., Srinivasan, R., Karthikeyan, R., and Smith, P.: Hydrological Modeling of Highly Glacierized Basins (Andes, Alps, and Central Asia), Water, 9, 111, 2017.

Paul, F., Maisch, M., Rothenbühler, C., Hoelzle, M., and Haeberli, W.: Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling, Global and Planetary Change, 55, 343-357, https://doi.org/10.1016/j.gloplacha.2006.08.003, 2007.

Pagliero, L., Bouraoui, F., Willems, P., and Diels, J.: Large-Scale Hydrological Simulations Using the Soil Water Assessment Tool, Protocol Development,and Application in the Danube Basin, Journal of Environmental Quality, 43, 145–154, http://dx.doi:10.2134/jeq2011.0359, 2014.
Rahman, K., Maringanti, C., Beniston, M., Widmer, F., Abbaspour, K., and Lehmann, A.: Streamflow Modeling in a Highly Managed Mountainous Glacier Watershed Using SWAT: The Upper Rhone River Watershed Case in Switzerland, Water Resour. Manag., 27, 323-339, 10.1007/s11269-012-0188-9, 2013.

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Reviewer 2

Dear Anonymous referee, thank you for your review and very constructive comments.

General remarks

Reviewer: Even though the paper is about important issues in hydrology (model complexity, impact of climate change), the current version has several flaws. As pointed out by Guillaume Thirel, its main goal is not clearly stated. You state that SWAT "has rarely been used for high alpine areas" and imply to study the suitability of SWAT for such environment. This is not completely true, as SWAT has been widely used in mountainous regions during the last decade (see for example Rahman et al. 2013, references within and papers citing it). The authors should carefully streamline the main goal of the paper.

Authors: You are right that the main goal of the paper is not clear. In this manuscript, we wanted to show not only the applicability of SWAT on a glacierised watershed but also to assess its transferability in different spatial and temporal scale and subsequently to test whether it can be applied on a high altitude glacierised ungauged watershed for runoff simulation and climate change simulations. This is something that hasn't been done before with SWAT but can be quite useful in water management considering the fact that SWAT is a widely used model, used even in large scale simulations (Pagliero et al, 2014).

It is true that in the last years there is an increasing interest in the application of SWAT in high mountainous areas and since a big part of the watersheds in these regions is ungauged, we believe that our study can contribute towards this direction. In our site we have the opportunity to test the upscaling of the model, because we have a quite unique situation; a small well gauged watershed monitored through the CZO projects, which is part of a larger watershed and for which we have hydrological data thanks to its use forthe hydroelectric power plant. This gives us the opportunity to verify the model with independently collected data on the large watershed.

We have rewritten the abstract and conclusions, and extended the introduction focusing on the points mentioned above in order to make our objectives clearer. We also added relevant literature to put them into perspective.

Reviewer: A second major problem is the lack of references or justifications throughout the text. You make strong statements without justifying them or explaining why you made that choice. Here are a few examples:

• The calibration and validation periods are both very short (line 181-183). Why have you chosen such a limited period?

Authors: The reason why the calibration and validation periods are short is that for the Damma glacier watershed we had runoff data for the period 2009-2013. Probably it would be best if we had used these runoff data only for calibration and omitted the validation step, but the performance of the calibration is the same as the calibration and therefore we think that it wouldn't make any difference. In addition, this period is short, but it still includes a relatively large variability in the weather conditions and precipitation amounts. For example, it includes a rather wet year and hot summer and dry and warm autumn.

Reviewer: You estimate the glacier retreat during the last 90 years (line 63-64) without any reference. Where does it come from?

Authors: Damma glacier watershed is a well studied site. Glacier retreat was estimated in previous studies described in Bernasconi et al., 2008 and Bernasconi et al., 2011 (already cited in the paragraph) using systematic recordings.

Reviewer: • Climate models (line 147-151): why have you chosen these 3 models out of the 10 available in CH2011? is there any reason?

Authors: We used these three models, because they were the ones in common with both ALPINE3D and PREVAH.

Reviewer: To the best of my knowledge, the CH2011 scenarios (based on the delta change method) were not suitable for assessing changes in extreme events. Based on which element, are you stating an increase in extreme events (Line 342-343)?

Authors: What we meant is that predicted runoff of the far future period T2 shows higher fluctuations from year to year than that of the near future period especially from September to October. Sentence is rephrased.

Reviewer: You are making strong assertions based on the Nash-Sutcliffe model efficiency throughout the paper (line 197-198, 250-251, 259, 268), but be careful, because this indicator strongly depends on the hydrological regime (Schaefli and Gupta, 2007). In alpine basins where you have a strong annual cycle, a NSE coefficient of 0.49 is rather bad and not satisfactory as you state. When comparing averaged models results (Figure 6, line 284-292), based on which elements (objective/subjective) can you say that the performance of SWAT is comparable to PREVAH and Alpine3D? I personally do not agree based on the NSE coefficients you provided.

Some of the SWAT parameters seem to be scale-dependent (in time and space), which could partly explain the model performance deterioration. You should somehow discuss which parameters are the most sensitive in space (validation over the Göschneneralpsee) and in time (with regard to climate scenarios). In addition, you are using different soil and landuse maps in the Damma and Göschneneralpsee catchments (Line114-122). For me, this choice is a bit risky as you upscale your parameters and could bring some inconsistency

Authors: In response to your comment and the comment by the Editor, we investigated further the predictive power of the model for the greater catchment by comparing the observed data with the model results for the spring snowmelt timing, timing of highest flow, autumn recession period and the centre of mass (COM). To do this analysis we used the 15-day average of the daily runoff. Results are presented in Fig. 1 and 2 and the Table 1 given below.

The model predicts efficiently the spring snowmelt timing and the autumn recession period. The difference between the COM of the observed and the simulated runoff, which is given in Table 1 here (Table 2 in the manuscript), is low and for some years close to zero, which is also satisfactory. The main inconsistencies between measured and simulated data are observed for the general timing of the highest peak, Fig. 2 (Table 2 in the manuscript).

One of the reasons for the deterioration of the model is that it doesn't differentiate between snow and glacier dynamics and only one parameter for both snowmelt and glacier meltrates is applied. This becomes more important in our study, since there is a difference between the glacier coverage of the two catchments. The Damma glacier is 50% covered by the glacier while the greater catchment is 20%.

One more reason is the difference in the response of the Damma glacier watershed in comparison to the greater area. Damma is characterised by very steep slopes (even up to nearly 80 degrees) and runoff originates mainly from snowmelt, glacier melt and rainfall (Magnuson et al., 2012). For this reason, the small watershed is characterised by very fast response, which led to the high value of ALPHA_BF and the low value of the GW_Delay parameters. On the other hand, the Göscheneralpsee feeding area is less steep on average and for the two out of the four of its watersheds, runoff is drained through tunnels into the reservoir.

The most sensitive parameters are the ones related to the snowmelt, like SFTMP, SMTMP and TIMP. During the manual calibration we checked many of the parameters related to landuse and soils and we think that we do not have an inconsistency. The parameter values set during the delineation of the watershed and initial parameterisation should be adequate. Finally, because our site is above tree line evapotranspiration parameters are not significant.

It is true that comparing SWAT with Alpine3D and PREVAH is tricky since they were calibrated for different catchments and different periods of time. The NS efficiency and the benchmark efficiency BE (added in the revised text)for the calibration period only are: 0.85 and 0.19 respectively for ALPINE3D, 0.91 and 0.49 for PREVAH and 0.84 and 0.22 for SWAT. These efficiencies of Alpine 3D and SWAT are in good agreement, with the efficiencies of PREVAH being slightly higher.

We have rewritten the entire paragraph for the comparison of the models. We focused less on comparing the efficiency of the model and mainly on what we can conclude from the comparison between the three models.

Minor remarks

Reviewer: Some typos are visible throughout the paper, the authors should carefullyproofread it.Here are some minor comments:

Authors: Corrected

Reviewer:1. Line 44: what do you mean by "its structure is physically based"? For me, Alpine3D is a physically based model, SWAT is not. Please clarify!

Authors: It really depends on how you define the term “physically based”. Some researchers consider SWAT to be a physically based model and others don’t since not all of its parameters can be defined directly by measurements. Since it wasn’t adding to the context, the sentence was deleted.

Reviewer:2. Line 98: what do you mean exactly by this statement?

Authors: L. 115 (former L. 98) Fontaine et al., (2002) revealed the importance of improving SWAT algorithms to include in the model the influence of elevation and season on the dynamics of the snowpack.

Reviewer: 3. Line 104: "basic input" is a subjective statement.

Authors: Line 122 (former L. 104) “basic” is deleted

Reviewer: Line 124: the new MeteoSwiss network is named SwissMetNet not ANETZ anymore.

Authors: Corrected

Reviewer: 5. Line 1341-134: you are right, lapse rate are critical in mountainous regions, so tell the reader which values you have used in you study!

Authors: Line 148. precipitation lapse rate PLAPS was set to 5 (mm/km) and temperature lapse rate was set to -5.84 (^{o}C/km).

Reviewer: 6. In figure 1, what is the added value of the inset for the present study? There is aninconsistency in the orientation (North) between figure 1 and 2. You should justcombine them into a single figure.

Authors: You are right. Figures 1 and 2 were combined to Figure 1.

Reviewer: 7. Figure 3a, is it really useful to show the uncalibrated time series?

Authors: Figures 3 and 4 were combined to one, Figure 2 and the uncalibrated time series was not included.

Reviewer: 8. We can hardly see the difference between the two curves in figure 5a. Consequently, the reader cannot really assess the quality of the model

Authors: A better version of Fig. 5a is given below in Fig. 3. (Fig. 3 in the manuscript). As you can see this Figure, there is an overestimation of the streamflow by the model during the years 2000 to 2002. This overestimation must be related to the runoff melt rate that 1999-2002 was a rather wet period. Furthermore, the simulated runoff peaks are higher and narrower than the observed ones, which must be related to the differences in the response and groundwater interactions between the small watershed and the greater area, as discussed above.

Reviewer: 9. In figure 6, it is somehow hard to make the difference between the lines. Try different colors.

Authors: Figure 6 is Figure 4 in the revised manuscript and a different colour scheme was applied.

References

Bernasconi, S. M., Christl, I., Hajdas, I., Zimmermann, S., Hagedorn, F., Smittenberg, R. H., Furrer, G., Zeyer, J., Brunner, I., Frey, B., Plotze, M., Lapanje, A., Edwards, P., Venterink, H. O., Goransson, H., Frossard, E., Bunemann, E., Jansa, J., Tamburini, F., Welc, M., Mitchell, E., Bourdon, B., Kretzschmar, R., Reynolds, B., Lemarchand, E., Wiederhold, J., Tipper, E., Kiczka, M., Hindshaw, R., Stahli, M., Jonas, T., Magnusson, J., Bauder, A., Farinotti, D., Huss, M., Wacker, L., Abbaspour, K., and Biglink Project, M.: Weathering, soil formation and initial ecosystem evolution on a glacier forefield: a case study from the Damma Glacier, Switzerland, Mineral. Mag., 72, 19-22, 10.1180/minmag.2008.072.1.19, 2008.

Bernasconi, S. M., Bauder, A., Bourdon, B., Brunner, I., Bunemann, E., Christl, I., Derungs, N., Edwards, P., Farinotti, D., Frey, B., Frossard, E., Furrer, G., Gierga, M., Goransson, H., Gulland, K., Hagedorn, F., Hajdas, I., Hindshaw, R., Ivy-Ochs, S., Jansa, J., Jonas, T., Kiczka, M., Kretzschmar, R., Lemarchand, E., Luster, J., Magnusson, J., Mitchell, E. A. D., Venterink, H. O., Plotze, M., Reynolds, B., Smittenberg, R. H., Stahli, M., Tamburini, F., Tipper, E. T., Wacker, L., Welc, M., Wiederhold, J. G., Zeyer, J., Zimmermann, S., and Zumsteg, A.: Chemical and Biological Gradients along the Damma Glacier Soil Chronosequence, Switzerland, Vadose Zone J., 10, 867-883,http://dx.doi:10.2136/vzj2010.0129, 2011.

Kobierska, F., Jonas, T., Zappa, M., Bavay, M., Magnusson, J., and Bernasconi, S. M.: Future runoff from a partly glacierized watershed in Central Switzerland: A two-model approach, Advances in Water Resources, 55, 204-214, http://dx.doi.org/10.1016/j.advwatres.2012.07.024, 2013.

Pagliero, L., Bouraoui, F., Willems, P., and Diels, J.: Large-Scale Hydrological Simulations Using the Soil Water Assessment Tool, Protocol Development,and Application in the Danube Basin, Journal of Environmental Quality, 43, 145–154, http://dx.doi:10.2134/jeq2011.0359, 2014.

Table 1 Difference of the centre of mass (COM) and autumn recession period in days, calculated from the 15-day average.

Year	COM	Autumn recession period
1997	6.8	1
1998	4.2	1
1999	1.0	0
2000	3.0	16
2001	0.6	1
2002	7.8	19
2003	0.6	5
2004	2.4	4
2005	4.3	0
2006	4.1	1
2007	8.1	1
2008	3.1	0
2009	4.6	0
2010	6.0	0

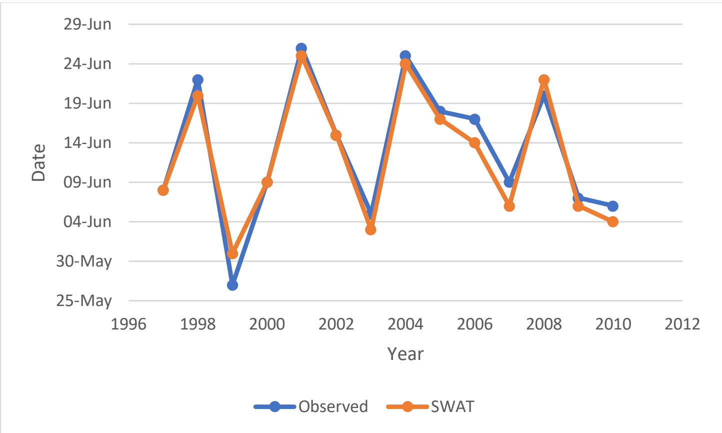

Figure 1 Comparison between the observed and simulated spring snowmelt timing. A 15-day average filter was applied on daily measurements.

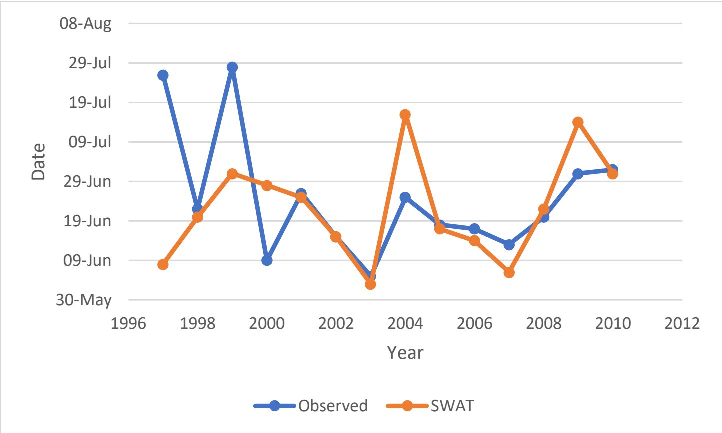

Figure 2 Comparison between the observed and simulated spring snowmelt timing. A 15-day average filter was applied on daily measurements.

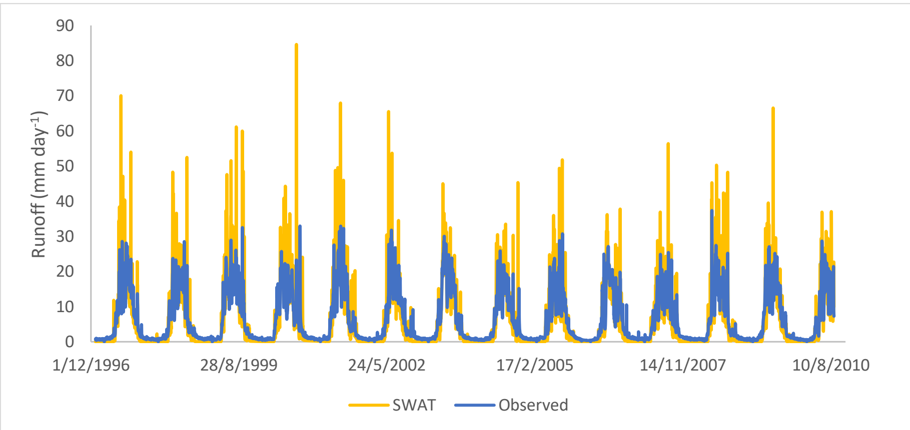

Figure 3(Figure *3*a in manuscript) SWAT results and measured runoff values of the feeding catchment of the Göscheneralpsee for the period 1997-2010

Assessment of SWAT spatial and temporal transferability for high altitude glacierised catchments

Maria Andrianaki[1], Juna Shrestha[1], Florian Kobierska[2], Nikolaos P. Nikolaidis[3], Stefano M. Bernasconi[1]

[1] Geological Institute, ETH Zurich, 8092 Zürich, Switzerland
[2] Agroscope, Reckenholzstrasse 191, CH-8046 Zürich
[3] Department of Environmental Engineering, Technical University of Crete, 73100 Chania, Greece

Correspondence to: Maria Andrianaki (mandrianaki@hotmail.com)

Abstract. In this study, we investigated the application and the transferability of the Soil Water and Assessment Tool (SWAT) in a partly glacierised alpine catchment, characterised by extreme climatic conditions and steep terrain. The model was initially calibrated for the 10 km^2 watershed of the Damma glacier Critical Zone Observatory (CZO) in central Switzerland using monitoring data for the period of 2009–2011 and then was validated with the measurements collected during 2012–2013 in the same area. Model performance was found to be satisfactory against both the Nash Sutcliffe criterion (NS) and a benchmark efficiency (BE). The transferability of the model was assessed by using the parameters calibrated on the small watershed and applying the model to the approximately 100 km^2 catchment that drains into the hydropower reservoir of the Göscheneralpsee and includes the Damma glacier CZO. Model results were compared to the reservoir inflow data from 1997 to 2010 and it was found that the model predicted successfully snowmelt timing and autumn recession but could not accurately capture the peak flow for certain years. Runoff was slightly overestimated from late May to June, when it is dominated by snowmelt, due to the fact that only one melt factor for both snowmelt and glacier melt was used. Finally, we investigated the response of the greater catchment to climate change using three different climate change scenarios and the results were compared to those of a previous study, where two different hydrological models, PREVAH and ALPINE 3D, were used. Predicted changes in future runoff and peak flow as well as seasonal dynamics are similar between the two studies. It is concluded that the methodology presented here, where SWAT is calibrated for a small watershed and then applied for a bigger area with similar climatic conditions and geographical characteristics, could work even under extreme conditions like ours. However, a greater attention should be given to the differences between glacial melt and snowmelt dynamics, since our findings indicate that the performance of the model as well as its transferability could be improved if different parameters for snowmelt and glacial melt were applied.

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 in water management (i.e. Arnold et al., 1998; Abbaspour et al., 2007). Climate change simulations provide crucial information for the assessment of its impact on water resources, water quality, and aquatic ecosystems (Farinotti et al., 2012; Aili et al., 2019). However, watershed modelling in high altitude alpine areas is rather challenging due to the rough terrain, heterogeneous land cover, extreme climatic conditions and glacier dynamics (Viviroli and Weingartner, 2004; Farinotti et al., 2012; Rahman et al., 2013), with the main challenge to be the lack of observed

hat gelöscht: 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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hat gelöscht: for the simulation of runoff in the partly glacierised watershed of the Damma glacier Critical Zone Observatory (CZO), Switzerland. The

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hat gelöscht: 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.

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and sufficient quality data in ungauged watersheds (Sivapalan et al., 2003; Viviroli et al., 2009b; Bocchiola et al., 2011).

Modelling and predicting the runoff of ungauged watersheds is one of the big challenges that hydrologists face today (Sivapalan et al., 2003; Hrachowitz et al., 2013). A common approach to address this problem is to calibrate a hydrological model for a gauged watershed using observed data and then transfer the model to the ungauged watershed by transferring the model parameters (Merz and Blöschl, 2003; Sivapalan et al., 2003). A great number of methods have been suggested for transferring model parameters, which include regression techniques between the model parameters and catchment attributes (e.g. Parajka et al., 2005; Deckers et al., 2010; Zhang et al., 2018) and similarity approaches such as spatial proximity and physical similarity (e.g. Bárdossy, 2007; Wagener et al., 2007; Patil and Stieglitz, 2014). However, as Thirel et al. (2015) point out, it is essential to asses and evaluate the ability of the hydrological models to perform efficiently under conditions different from those in which they were developed or calibrated.

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). It is equipped with a snowmelt 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. Although there is an increasing interest in applying SWAT on snow-dominated (Grusson et al., 2015) and glacierised watersheds (Rahman et al., 2013; Garee et al., 2017; Omani et al., 2017), its transferability under the extreme conditions of these high altitude environments has not been tested yet. In this study, we have a quite unique situation of a small well gauged watershed, the Damma glacier watershed, which is part of the larger catchment feeding the Göscheneralpsee reservoir, for which we have hydrological data thanks to its use by the hydroelectric power plant. This way we were able to assess the transferability and upscaling of SWAT, by calibrating the model for the Damma glacier watershed and then transferring it to the greater area feeding the Göscheneralpsee reservoir. Subsequently, climate change simulations were conducted in order to assess the transferability of the model on a temporal scale. The assessment was conducted by comparing our findings with those of a previous study for the same area, which used two other hydrological models with different characteristics, PREVAH and ALPINE3D (Kobierska et al., 2013).

2 Study Site

The Damma glacier watershed (Fig. 1a) is situated in the central Swiss Alps in Switzerland and was one of the Critical Zone Observatories established within the European project SoilTrEC (Banwart et al., 2011). It is located at an altitude between 1790 m and 3200 m above sea level, has a total area of 10 km^2 and a typical alpine climate with an average yearly temperature of 1 ºC and yearly precipitation of 2400 mm (Kobierska et al., 2013). Damma

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

hat gelöscht: 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.

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hat gelöscht: 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.¶

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glacier covers 50 % of the watershed and due to climate change has retreated at an average rate of 10 m per year in the last 90 years. However, during 1920–1928 and 1970–1992 the recession was interrupted and the glacier grew, resulting in two moraines (Kobierska et al., 2011). After the retreat of the glacier a soil chronosequence is developed, which has a total length of 1 km (Bernasconi et al., 2008; Bernasconi et al., 2011; Kobierska et al., 2013). 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. 1b) is a hydropower reservoir of a volume of 75 million m^3. A 100 km^2 and 20 % glacier covered catchment drains into the reservoir. It includes the watersheds of the Damma, Chelen and Tiefen glaciers and the Voralptal watershed. The Tiefen glacier and Voralptal watersheds do not drain directly into the reservoir but their runoff is redirected through two tunnels. The site is described extensively in Kobierska et al. (2013).

3 Model 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-land use 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 land use, soil parameters, and weather conditions. The water is stored in four storage volumes: snow, soil moisture, shallow aquifer and deep aquifer. The processes 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. The factors controlling snow melt are the air and snowpack temperature, the melting rate and the area covered by snow. The updated snow cover model takes into account shading, drifting, topography and landcover to create a nonuniform snow cover (Neitsch et al., 2011). Furthermore, runoff from frozen soil can also be calculated by defining if the temperature in the first soil layer is less than 0°C. 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 found in detail in Arnold et al. (1998) and Srinivasan et al. (1998).

Snow processes in high alpine areas are strongly influenced by the terrain features (Ahl et al., 2008; Zhang et al., 2008). Fontaine et al. (2002) revealed the importance of improving SWAT algorithms to include in the model the

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influence of elevation and season on the dynamics of the snowpack. They found that the definition of elevation bands within the model subbasins can significantly improve the performance of the model in watersheds at high altitudes and with large elevation gradients. With the improved snow melting algorithm (Fontaine et al., 2002), streamflow in alpine regions can be successfully simulated by SWAT (Rahman et al., 2013; Grusson et al., 2015; Omani et al., 2017).

3.2 Input data

The input data required by SWAT are: topography, soil, land use and meteorological data.

3.2.1 Topography

The topography of both study areas was defined using a high precision Digital elevation model (DEM) with 2 m grid cells (swissALTI3D), produced by the Swiss Federal office for Topography (http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/height/swissALTI3D.html).

3.2.2 Soil and land use map

In order to better describe the glacier forefield and to reduce the uncertainty of the calibration for the Damma glacier watershed, detailed soil and land use maps were created 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 feeding the Göscheneralpsee, the soil map used, was produced and provided by the Swiss Federal Statistical Office at a scale of 1:200,000 (http://www.bfs.admin.ch/bfs/portal/en/index.html). For land use, 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 SwissMetNet network were used. 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. The precipitation and temperature lapse rate parameters of the model are PLAPS and TLAPS and were set to 5 mm km^{-1} and -5.84 °C km^{-1} respectively.

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

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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 delta-change method was used for the creation of the datasets (Bosshard et al., 2011). 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 scenarios respectively. The CNRM, ETHZ and SHMI scenarios were chosen to be in agreement with the previous study of Kobierska et al. (2013), to be able to carry out a direct comparison of the three models. The following periods were selected:

Reference period (T0): 1981–2010

Near future period (T1): 2021–2050

Far future period (T2): 2070–2099

Similarly to 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 for different sites in the Alps (Bavay et al., 2013; Farinotti et al., 2012).

3.2.4 Runoff data

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

3.2.5 Glacier extent

Data on the glacier extent for the present period but also for the two periods of the climate change scenarios were provided by Paul et al (2007). They 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

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subbasin and for each elevation band. The initial snow is given as the snow water equivalent 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.

4 Methodology

The purpose of this study is to assess the transferability of SWAT in temporal and spatial scales at a high altitude alpine and glacierised site. This way it is tested whether the model can be transferred and is capable for the simulation of runoff but also for further climate change studies on an ungauged glacierised watershed. Furthermore, this methodology tests its robustness under these extreme climatic and geographical conditions. For this reason, SWAT was initially calibrated for the small Damma watershed, which is well monitored through the CZO projects, and then it was upscaled and applied for the greater area feeding the Göscheneralpsee reservoir and includes the Damma glacier watershed. The upscaling of the model was verified by comparing model results with the reservoir data provided by the managing company.

Since the Damma glacier watershed is part of the greater Göscheneralpsee feeding catchment, the parameters of the model were transferred using the spatial proximity approach, with no further regionalisation procedure. In this case, the initial setup of SWAT for the greater catchment was conducted using the input data presented in section 3.2 and only the parameters presented in Table 1 were changed to the calibrated values derived from the calibration of the Damma glacier watershed. The initial parameterisation of the model during the setup and the watershed delineation assisted in the transferability of the model since a number of parameters is already defined based on the topography, land use and soil data.

Subsequently, in order to assess its transferability on a temporal scale, climate change simulations were conducted and results were compared with those of a previous study for the same area, which used two other hydrological models with different characteristics, PREVAH and Alpine 3D (Kobierska et al., 2013).

This methodology is a modified version of the proxy-basin test introduced by Klemeš (1986), which is one of the proposed testing schemes for the enhancement of the calibration and validation procedure in hydrological modelling. According to Klemeš (1986) the proxy basin test can be used to test the geographical transposability of the model between two regions, for subsequent simulation of the streamflow in ungauged watersheds with similar characteristics. The model is calibrated and validated for two different but similar watersheds and if the results are acceptable it is then considered safe to be transferred and used at a third watershed with similar characteristics.

5 Model setup, calibration and validation

SWAT was initially setup for the Damma glacier CZO and the greater area feeding the Göscheneralpsee using the topography, soil and land use data presented in section 3.2. Following the delineation procedure, the Damma watershed and the greater area were divided into 5 and 25 subbasins respectively. By setting the lowest possible thresholds for land use, 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. The setup was complete with

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the addition of the meteorological input and the definition of the initial snow for each elevation band of each subbasin. For the climate change simulations, the meteorological input consists of the climate change scenarios described in section 3.2.3 and the initial snow that corresponds to the first year of each future period, as calculated by the glacier extent data described in section 3.2.5.

5.1 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. For the better identification of the parameters that influence the hydrology of the site the calibration was first conducted manually. The most sensitive parameters during this step were related to snow melt such as: i) TIMP, the snow pack temperature lag factor, ii) SMFMX, the snow melt factor on the 21st of June (mmH_2O / °C day^{-1}), iii) SMFMN, the snow melt factor on the 21st of December (mmH_2O / °C day^{-1}), CN_FROZ, which was set to active in order and finally the snow fall and snow melt temperatures SFTMP and SMTMP respectively. Because most of the subbasins of the Damma glacier watershed, delineated during the initial setup of the model, were partially glacier covered, it was decided to follow a simple approach and apply the same snow parameters for all the subbasins. This means that the same parameters were applied for both glacier and snow dynamics.

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 play an important role on the performance of the model. Evapotranspiration (ET) related parameters were not significant since our study site is above the tree line and ET is relatively minor.

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 is smaller than the standard deviation of the measured data. A model is considered calibrated when the chosen criterion between the best simulation and calibration data reaches the best value (Abbaspour et al., 2007). The parameters introduced in SWAT-CUP as well as their range are the ones that were identified during the manual calibration as the most important.

The criterion used for the calibration with SWAT-CUP is the Nash-Sutcliffe (Nash and Sutcliffe, 1970) model efficiency (NS), since it was the criterion available in SUFI-2 that is commonly used in hydrological studies. The NS shows the relationship between the measured and the simulated runoff (Eq. 1). The performance of the calibrated model was further evaluated by the square of Pearson's product moment correlation R^2, which represents the proportion 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).

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

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where y is the individual observed value, $\hat{y}$ for the individual simulated value and $\bar{y}$ the mean observed value. However, as Schaefli and Gupta (2007) pointed out, the NS criterion is not enough to judge the efficiency of the model when simulating runoff with high seasonality like the one in high altitude watersheds. Therefore, as an additional criterion for the performance of the model, a benchmark efficiency indicator was calculated, according to Eq. 2:

$$BE = 1 - \frac{\sum_{t=1}^{n}[q_{obs}(t) - q_{sim}(t)]^2}{\sum_{t=1}^{n}[q_{obs}(t) - q_b(t)]^2}, \qquad (2)$$

where q_{obs} is the observed runoff; q_{sim} is the simulated runoff by SWAT; and q_b is runoff given by the benchmark model. The calendar day model was chosen as benchmark (Schaefli and Gupta, 2007), which is the observed interannual mean runoff for every calendar day.

Table 1 shows the default and the after calibration values of the SWAT parameters that were changed during calibration. 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 / °C-day), the minimum melt factor, while the SMFMX is set to the value of 4.7 mmH_2O / °C-day. SURLAG and GW_DELAY play an important role 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 GW_DELAY was set 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 results of the calibrated model for the daily runoff and the observed data are presented in Fig. 2(a), while cumulative runoff is presented in Fig. 2(c). The fit of the model to the observed data is satisfactory and the results of the calibrated model matched the observed data throughout most of the year. The graph of the cumulative runoff (Fig. 2c) 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 warm and dry months of September, October and November which resulted in a slight underestimation of the runoff. Overall SWAT performance for the calibrated period is considered very satisfactory since the NS efficiency is 0.84 and R^2 is 0.85. BE for this period is 0.22, a value that we consider to be satisfactory and is comparable to that of the previous model, calibrated for the greater area of Göscheneralpsee.

5.2 Sensitivity analysis

The automatic global sensitivity analysis was conducted with SWAT-CUP software and 17 input parameters were analysed. 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.

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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 f ...

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5.3 Model validation

SWAT was validated using the meteorological data for 2012 and 2013 and the results of the model as well as the measured runoff are presented in Fig. 2(b). Figure 2(d) presents the cumulative graphs. The SWAT model for this period performed efficiently, similarly to the calibration period, with a Nash-Sutcliffe efficiency of 0.85, R^2 0.86.and the BE 0.25. A small inconsistency is observed in the late spring of 2012, when estimated runoff is underestimated, probably due to the extremely wet May in that year that cannot be efficiently simulated. Although, due to the lack of longer monitoring data, the total calibration-validation period 2009-2013 is short, it still includes a relatively large variability in the weather conditions and precipitation amounts and despite this variability the overall model performance is very satisfactory. The small seasonal differences in model performance are due to the evolution of runoff generation throughout the season: runoff in spring and early summer (May, June) comes mainly from snowmelt while in July and August it stems mainly from glacier melt. Although there are two different water sources during the two different periods, we can only assign one set of parameters. We can nevertheless conclude that SWAT can be successfully applied for a partly glacierised watershed.

6 Results and Discussion

6.1 Upscaling SWAT to the greater catchment feeding the Göscheneralpsee reservoir

The results of the model for the greater area that feeds the Göscheneralpsee, are presented in Fig. 3(a) together with the measured inflow in the reservoir. The observed and predictive cumulative flow is presented in Fig. 3(b). Model performance criteria were lower than for the calibration period as NS dropped to 0.49 and the R^2 to 0.72. The cumulative graph shows that there is an overall good agreement between model results and the measured reservoir inflow. Both Figures 3(a) and 3(b) show that there is an overestimation of total runoff for the period 1999-2002, which appears to be linked to the higher precipitation amounts during this period. Measured precipitation measured at Gütsch weather station for this period is up to 46 % higher than the average precipitation of 1981-2010.

The predictability of the model was further tested by analysing key parameters related to median runoff such as spring snowmelt timing, timing of peak flow, autumn recession period and the centre of mass (COM), which can indicate temporal shifts in the hydrological regime. Table 2 shows the difference in days between the observed and simulated values of the above parameters for each year of the period 1997-2010. A 15day moving average window was applied to daily runoff. Snowmelt timing and autumn recession are predicted successfully since the differences for most years are zero or close to zero, except for 2000 and 2002 for autumn recession. Peak flow timing shows some inconsistencies between observed and simulated data for certain years, which are mainly related to the fact that for these years and during the snowmelt period, SWAT produces results with higher peaks. Finally, the COM of the simulated data is in good agreement with that of the observed data, with an average difference of 4 days.

On the whole, SWAT performance is considered to be satisfactory and it was successfully transferred to the greater Göscheneralpsee feeding catchment. One of the main reasons for the deterioration of the model performance during the years with higher precipitation, 1999-2002, is that SWAT doesn't differentiate between snow and glacier dynamics and only one parameter for both snowmelt and glacial melt rate was applied. This becomes more

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hat nach oben verschoben [6]: 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.

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important in our study, since there is a difference between the percentage of glacial coverage of the two catchments, with the Damma glacier watershed being 50% covered while the greater catchment 20%. In Omani et al. (2017) this issue was partly addressed by applying different snow parameters to the glacier covered subbasins. However, the subbasins in our calibration watershed, the Damma glacier watershed, were partly glacierised and for this reason it was decided to apply only one set of snow parameters for the whole watershed.

Furthermore, some inconsistency is caused by the fact that for the two out of the four of the watersheds of the greater area feeding the Göscheneralpsee, runoff is drained through tunnels into the reservoir. In addition, there is a difference in the hydrological response between the Damma glacier watershed in comparison to the greater area. Damma is characterised by very steep slopes (even up to nearly 80 degrees) and runoff originates mainly from snowmelt, glacial melt and rainfall (Magnuson et al., 2012). The ALPHA_BF parameter of SWAT was set to a high value and the GW_DELAY to low, parameter trends that characterise a watershed with a high response. On the other hand, the Göscheneralpsee feeding area is less steep on average. The combination of these two factors might be the reason, why some of the simulated peaks are higher but also narrower compared to the observed inflows into the reservoir.

Finally, SWAT results were compared to results from PREVAH and ALPINE3D models, already published in Magnusson et al. (2011) and Kobierska et al. (2013) (Fig. 4). 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).

Figure 4 shows the interannual average of the period 1997-2010 daily runoff for each model. SWAT overestimated the runoff of the snowmelt period, from May to the beginning of July, while from mid July to late September its results are close to the observed values and in agreement with the other two models. Finally, in October runoff is slightly underestimated. The seasonality in variation between model results and observed values is linked to the application of only one melt rate for both snowmelt and glacial melt periods. The best fit of the model is observed when glacial melt is the major contributor to runoff, while it is overestimated during the snowmelt period, which is the reason of the excessive simulated runoff during the 1999-2002 period of high precipitation (Fig.3), as discussed above. Seasonal variability in model performance is observed not only for SWAT but also for ALPINE3D and PREVAH, as ALPINE3D underestimated runoff during the snowmelt period, from May to June, while on the other hand runoff was slightly overestimated by PREVAH in October and November (Kobierska et al., 2013).

Furthermore, a combination of the factors discussed above about the applied snowmelt parameters and the deviation in hydrological response between the two areas because of human intervention and topographical/geographical features is the reason why SWAT doesn't simulate efficiently the winter low flows.

6.2 SWAT transferability on a temporal scale

As a next step, we assessed whether SWAT can be transferred at a temporal scale, by running climate change scenarios for the greater area that feeds the Göscheneralpsee. In order to verify the model transferability, results were compared with the climate change study in Kobierska et al. (2013) using the same time periods as follows:

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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.¶

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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 interannual average runoff for each different scenario along the whole period in Fig. 5(a) for the near and in Fig. 5(b) for the far future periods.

During the reference period runoff peaks in early July when snowmelt is combined with glacier melt. For the near future period T1, the main difference happens 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 compensate the predicted decrease in precipitation. From September until the end of the season, simulated stream flow of all scenarios is higher than the reference period, which is explained by the higher predicted precipitation during autumn. The annual peak remains in early July, since the glacier has not melted away yet, providing glacier melt.

For the far future period T2, runoff from spring to June is predicted to increase significantly for all three scenarios due to more intense snowmelt. In addition, higher precipitation is predicted by the climatic data for this period. Based on the available glacier extent data described in section 3.2.5, we estimated that in 2070, the total glacier volume will be reduced to almost half, resulting in less glacial 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 will extend until December instead of September.

At the end of the T2 period, the average temperature increase in our site will be 3.35°C and only a small part of the glacier will remain in high elevation. The date of peak flow will shift to be in the beginning of June. The main runoff volume 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 scenarios in T2 period is predicted to decrease.

To better observe the seasonal changes of estimated runoff, Fig. 6 shows the interannual 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. 6(a). The increase is higher in the far future 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 change scenarios predict a significant decrease in precipitation, which is also depicted in the predicted runoff. The scenario that has the most drastic effect is the ETHZ because it is the scenario that predicts the highest increase in the temperature and decrease in the precipitation. For September and October, results do not show a clear trend for the warmer ETHZ scenario, however for the CNRM and SHMI scenarios, predicted runoff is lower than the reference. Finally the predicted

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runoff of the far future period T2 shows higher fluctuations from year to year than that of the near future period especially from September to October.

The climate change predictions of SWAT and the subsequent conclusions show many similarities in the seasonal variations with that of ALPINE3D and PREVAH. This observation is very promising since it demonstrates that SWAT could be applied to climate change studies in ungauged high altitude watersheds. There are however uncertainties and differences between the models. ALPINE3D and PREVAH models predict the spring peak flow to shift approximately by 3 and 6 weeks for the near and far future periods respectively. On the other hand, the shift in peak flow with SWAT is smaller and especially for the near future period a 10 day shift is predicted only with the warmer ETHZ scenario (Fig. 5).

7 Conclusions

This study is an assessment of the transferability or upscaling of SWAT on a spatial and temporal scale for a partly glacierised catchment at a high altitude. For this reason, we followed an approach similar to the proxy-basin test introduced by Klemeš (1986).

Firstly, SWAT was calibrated and validated for the Damma glacier watershed and it was demonstrated that despite the extreme conditions of this high alpine watershed, SWAT performed successfully, with satisfactory NS and BE efficiencies. Subsequently, we assessed the transferability of the model by upscaling and applying SWAT for the greater area that drains into the Göscheneralpsee reservoir and includes the Damma glacier watershed. By comparing model results with existing inflow data, we showed that the model was able to predict key parameters such as the snowmelt timing, autumn recession period and the peak flow timing. However, overestimation of runoff during the snowmelt period, especially in wet years, highlights the importance of taking into account the difference in snow and glacier dynamics. It showed that better performance could have been achieved if different parameters for snow and glacial melt had been applied. This observation is quite important for study sites where streamflow is greatly dependent on both snow- and glacier melt. Model performance was potentially affected in the greater catchment due to hydropower infrastructure such as tunnels.

The temporal transferability of SWAT was analysed by assessing the impact of climate change on the hydrology of the greater catchment and comparing these results with a previous climate change study conducted for the same area. Climate change predictions showed that the hydrological regime will change significantly in the future especially towards the end of the century. Daily runoff during May and June is predicted to increase because more intense snowmelt and the predicted wetter springs. Projected runoff from July to October, mainly for the far future period but also for the near future, is significantly decreased. These results show many similarities with those previously published.

In conclusion, our findings indicate that SWAT is a model that can be successfully transferred to simulate streamflow and climate change impact for high altitude glacierised ungauged watersheds. The upscaling methodology used here, where SWAT is calibrated for a small watershed and then applied for a greater area that includes the calibration watershed, is a simple but still effective approach. It can be valuable in predicting

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hat gelöscht: 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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hat gelöscht: 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.¶

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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

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streamflow of ungauged watersheds, in large scale hydrological simulations and for policy makers working in water management.

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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References

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., and Srinivasan, R.: Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT, J. Hydrol., 333, 413-430, http://dx.doi.org/10.1016/j.jhydrol.2006.09.014, 2007.

Ahl, R. S., Woods, S. W., and Zuuring, H. R.: Hydrologic Calibration and Validation of SWAT in a Snow-Dominated Rocky Mountain Watershed, Montana, U.S.A., J. Am. Water Resour. As., 44, 1411-1430, 10.1111/j.1752-1688.2008.00233.x, 2008.

Aili, T., Soncini, A., Bianchi, A., Diolaiuti, G., D'Agata, C., Bocchiola, D. J. T., and Climatology, A.: Assessing water resources under climate change in high-altitude catchments: a methodology and an application in the Italian Alps, Theor. Appl. Climatol., 135, 135-156, 10.1007/s00704-017-2366-4, 2019.

Andrianaki, M., Bernasconi, S. M., and Nikolaidis, N. P.: Chapter Eight - Quantifying the Incipient Development of Soil Structure and Functions Within a Glacial Forefield Chronosequence, in: Advances in Agronomy, edited by: Steven, A. B., and Donald, L. S., Academic Press, 215-239, 2017.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: Large area hydrologic modeling and assessment - Part 1: Model development, J. Am. Water Resour. As., 34, 73-89, 10.1111/j.1752-1688.1998.tb05961.x, 1998.

Banwart, S., Bernasconi, S. M., Bloem, J., Blum, W., Brandao, M., Brantley, S., Chabaux, F., Duffy, C., Kram, P., Lair, G., Lundin, L., Nikolaidis, N., Novak, M., Panagos, P., Ragnarsdottir, K. V., Reynolds, B., Rousseva, S., de Ruiter, P., van Gaans, P., van Riemsdijk, W., White, T., and Zhang, B.: Soil Processes and Functions in Critical

hat gelöscht: 1

hat gelöscht: JAWRA

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Zone Observatories: Hypotheses and Experimental Design, Vadose Zone J., 10, 974-987, 10.2136/vzj2010.0136, 2011.

Bárdossy, A.: Calibration of hydrological model parameters for ungauged catchments, Hydrol. Earth Syst. Sci., 11, 703-710, 10.5194/hess-11-703-2007, 2007.

Bavay, M., Grünewald, T., and Lehning, M.: Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland, Adv. Water Resour., 55, 4-16, https://doi.org/10.1016/j.advwatres.2012.12.009, 2013.

Bernasconi, S. M., Christl, I., Hajdas, I., Zimmermann, S., Hagedorn, F., Smittenberg, R. H., Furrer, G., Zeyer, J., Brunner, I., Frey, B., Plotze, M., Lapanje, A., Edwards, P., Venterink, H. O., Goransson, H., Frossard, E., Bunemann, E., Jansa, J., Tamburini, F., Welc, M., Mitchell, E., Bourdon, B., Kretzschmar, R., Reynolds, B., Lemarchand, E., Wiederhold, J., Tipper, E., Kiczka, M., Hindshaw, R., Stahli, M., Jonas, T., Magnusson, J., Bauder, A., Farinotti, D., Huss, M., Wacker, L., Abbaspour, K., and Biglink Project, M.: Weathering, soil formation and initial ecosystem evolution on a glacier forefield: a case study from the Damma Glacier, Switzerland, Mineral. Mag., 72, 19-22, 10.1180/minmag.2008.072.1.19, 2008.

Bernasconi, S. M., Bauder, A., Bourdon, B., Brunner, I., Bunemann, E., Christl, I., Derungs, N., Edwards, P., Farinotti, D., Frey, B., Frossard, E., Furrer, G., Gierga, M., Goransson, H., Gulland, K., Hagedorn, F., Hajdas, I., Hindshaw, R., Ivy-Ochs, S., Jansa, J., Jonas, T., Kiczka, M., Kretzschmar, R., Lemarchand, E., Luster, J., Magnusson, J., Mitchell, E. A. D., Venterink, H. O., Plotze, M., Reynolds, B., Smittenberg, R. H., Stahli, M., Tamburini, F., Tipper, E. T., Wacker, L., Welc, M., Wiederhold, J. G., Zeyer, J., Zimmermann, S., and Zumsteg, A.: Chemical and Biological Gradients along the Damma Glacier Soil Chronosequence, Switzerland, Vadose Zone J., 10, 867-883, 10.2136/vzj2010.0129, 2011.

Bosshard, T., Kotlarski, S., Ewen, T., and Schär, C.: Spectral representation of the annual cycle in the climate change signal, Hydrol. Earth Syst. Sci., 15, 2777-2788, 10.5194/hess-15-2777-2011, 2011.

CH2011: Swiss Climate Change Scenarios CH2011, published by C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC, Zurich, Switzerland, 88 pp., 2011.

Bocchiola, D., Diolaiuti, G., Soncini, A., Mihalcea, C., D'Agata, C., Mayer, C., Lambrecht, A., Rosso, R., and Smiraglia, C.: Prediction of future hydrological regimes in poorly gauged high altitude basins: the case study of the upper Indus, Pakistan, Hydrol. Earth Syst. Sci., 15, 2059-2075, 10.5194/hess-15-2059-2011, 2011.

Debele, B., Srinivasan, R., and Gosain, A. K.: Comparison of Process-Based and Temperature-Index Snowmelt Modeling in SWAT, Water Resour. Manag., 24, 1065-1088, 10.1007/s11269-009-9486-2, 2010.

Di Luzio, M., Srinivasan, R., and Arnold, J. G.: Integration of watershed tools and SWAT model into basins, J. Am. Water Resour. As., 38, 1127-1141, 10.1111/j.1752-1688.2002.tb05551.x, 2002.

Deckers, D. L. E. H., Booij, M. J., Rientjes, T. H. M., and Krol, M. S. J. W. R. M.: Catchment Variability and Parameter Estimation in Multi-Objective Regionalisation of a Rainfall–Runoff Model, Water Resour. Manag., 24, 3961-3985, 10.1007/s11269-010-9642-8, 2010.

Dumig, A., Smittenberg, R., and Kogel-Knabner, I.: Concurrent evolution of organic and mineral components during initial soil development after retreat of the Damma glacier, Switzerland, Geoderma, 163, 83-94, 10.1016/j.geoderma.2011.04.006, 2011.

Farinotti, D., Usselmann, S., Huss, M., Bauder, A., and Funk, M.: Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios, Hydrol. Process., 26, 1909-1924, doi:10.1002/hyp.8276, 2012.

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Fontaine, T. A., Cruickshank, T. S., Arnold, J. G., and Hotchkiss, R. H.: Development of a snowfall–snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT), J. Hydrol., 262, 209-223, http://dx.doi.org/10.1016/S0022-1694(02)00029-X, 2002.

Garee, K., Chen, X., Bao, A., Wang, Y., and Meng, F.: Hydrological Modeling of the Upper Indus Basin: A Case Study from a High-Altitude Glacierized Catchment Hunza, Water, 9, doi:10.3390/w9010017, 2017.

Grusson, Y., Sun, X., Gascoin, S., Sauvage, S., Raghavan, S., Anctil, F., and Sáchez-Pérez, J.-M.: Assessing the capability of the SWAT model to simulate snow, snow melt and streamflow dynamics over an alpine watershed, J. Hydrol., 531, 574-588, http://dx.doi.org/10.1016/j.jhydrol.2015.10.070, 2015.

Hock, R.: Temperature index melt modelling in mountain areas, J. Hydrol., 282, 104-115, http://dx.doi.org/10.1016/S0022-1694(03)00257-9, 2003.

Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., Arheimer, B., Blume, T., Clark, M. P., Ehret, U., Fenicia, F., Freer, J. E., Gelfan, A., Gupta, H. V., Hughes, D. A., Hut, R. W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P. A., Uhlenbrook, S., Wagener, T., Winsemius, H. C., Woods, R. A., Zehe, E., and Cudennec, C.: A decade of Predictions in Ungauged Basins (PUB)—a review, Hydrol. Sci. J., 58, 1198-1255, 10.1080/02626667.2013.803183, 2013.

Klemes, V.: Operational Testing of Hydrological Simulation-Models, Hydrol. Sci. J., 31, 13-24, https://doi.org/10.1080/02626668609491024, 1986.

Kobierska, F., Jonas, T., Magnusson, J., Zappa, M., Bavay, M., Bosshard, T., Paul, F., and Bernasconi, S. M.: Climate change effects on snow melt and discharge of a partly glacierized watershed in Central Switzerland (SoilTrec Critical Zone Observatory), Appl. Geochem., 26, Supplement, S60-S62, 10.1016/j.apgeochem.2011.03.029, 2011.

Kobierska, F., Jonas, T., Zappa, M., Bavay, M., Magnusson, J., and Bernasconi, S. M.: Future runoff from a partly glacierized watershed in Central Switzerland: A two-model approach, Adv. Water Resour., 55, 204-214, http://dx.doi.org/10.1016/j.advwatres.2012.07.024, 2013.

Lehning, M., Völksch, I., Gustafsson, D., Nguyen, T. A., Stähli, M., and Zappa, M.: ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology, Hydrol. Process., 20, 2111-2128, 10.1002/hyp.6204, 2006.

Magnusson, J., Farinotti, D., Jonas, T., and Bavay, M.: Quantitative evaluation of different hydrological modelling approaches in a partly glacierized Swiss watershed, Hydrol. Process., 25, 2071-2084, 10.1002/hyp.7958, 2011.

Magnusson, J., Jonas, T., and Kirchner, J. W.: Temperature dynamics of a proglacial stream: Identifying dominant energy balance components and inferring spatially integrated hydraulic geometry, Water Resour. Res., 48, W06510, doi:10.1029/2011WR011378, 2012.

Merz, R., and Blöschl, G.: Regionalisation of catchment model parameters, J. Hydrol., 287, 95-123, https://doi.org/10.1016/j.jhydrol.2003.09.028, 2004.

Nash, J. E., and Sutcliffe, J. V.: River flow forecasting through conceptual models part I — A discussion of principles, J. Hydrol., 10, 282-290, http://dx.doi.org/10.1016/0022-1694(70)90255-6, 1970.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R.: Soil and water assessment tool—Theoretical documentation—Version 2009, Texas Water Resources Institute technical report No. 406, Texas 77843-2118, 2011.

Omani, N., Srinivasan, R., Karthikeyan, R., and Smith, P.: Hydrological Modeling of Highly Glacierized Basins (Andes, Alps, and Central Asia), Water, 9, 111, 2017.

hat gelöscht: Farinotti, D., Usselmann, S., Huss, M., Bauder, A., and Funk, M.: Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios, Hydrological Processes, 26, 1909-1924, 10.1002/hyp.8276, 2012b.¶

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hat verschoben (Einfügung) [7]

Parajka, J., Merz, R., and Blöschl, G.: A comparison of regionalisation methods for catchment model parameters, Hydrol. Earth Syst. Sci., 9, 157-171, 10.5194/hess-9-157-2005, 2005.

Patil, S., and Stieglitz, M.: Modelling daily streamflow at ungauged catchments: what information is necessary?, Hydrol. Process., 28, 1159-1169, 10.1002/hyp.9660, 2014.

Paul, F., Maisch, M., Rothenbühler, C., Hoelzle, M., and Haeberli, W.: Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling, Global Planet. Change, 55, 343-357, https://doi.org/10.1016/j.gloplacha.2006.08.003, 2007.

Rahman, K., Maringanti, C., Beniston, M., Widmer, F., Abbaspour, K., and Lehmann, A.: Streamflow Modeling in a Highly Managed Mountainous Glacier Watershed Using SWAT: The Upper Rhone River Watershed Case in Switzerland, Water Resour. Manag., 27, 323-339, 10.1007/s11269-012-0188-9, 2013.

Schaefli, B., and Gupta, H. V.: Do Nash values have value?, Hydrol. Process., 21, 2075-2080, doi:10.1002/hyp.6825, 2007.

Schaltegger, U.: The central Aar granite – Highly differentiated calc-alkaline magmatism in the Aar massif (central Alps, Switzerland), Eur. J. Mineral., 2, 245-259, 1990.

Sivapalan, M., Takeuchi, K., Franks, S.W., Gupta, V.K., Karambiri, H., Lakschmi, V., Liang, X., McDonnel, J.J., Mendiondo, E.M., O`Connell, P.E., Oki, T., Pomeroy, J.W., Schertzer, D., Uhlenbrook, S. and Zehe E., IAHS Decade on Predictions in Ungauged Basins, PUB. 2003–2012: shaping an exciting future for the hydrological sciences. Hydrological Sciences Journal, 48 (6), 857–880, https://doi.org/10.1623/hysj.48.6.857.51421, 2003.

Srinivasan, R., Ramanarayanan, T. S., Arnold, J. G., and Bednarz, S. T.: Large area hydrologic modeling and assessment - Part II: Model application, J. Am. Water Resour. As., 34, 91-101, 10.1111/j.1752-1688.1998.tb05962.x, 1998.

Thirel, G., Andréassian, V., and Perrin, C.: On the need to test hydrological models under changing conditions, Hydrol. Sci. J., 60, 1165-1173, 10.1080/02626667.2015.1050027, 2015.

Viviroli, D. and Weingartner, R.: The hydrological significance of mountains: from regional to global scale, Hydrol. Earth Syst. Sci., 8, 1017-1030, https://doi.org/10.5194/hess-8-1017-2004, 2004.

Viviroli, D., Zappa, M., Schwanbeck, J., Gurtz, J., and Weingartner, R.: Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part I: Modelling framework and calibration results, J. Hydrol., 377, 191-207, http://dx.doi.org/10.1016/j.jhydrol.2009.08.023, 2009a.

Viviroli, D., Mittelbach, H., Gurtz, J., and Weingartner, R.: Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results, J. Hydrol., 377, 208-225, http://dx.doi.org/10.1016/j.jhydrol.2009.08.022, 2009b.

Wagener, T., Sivapalan, M., Troch, P., and Woods, R.: Catchment Classification and Hydrologic Similarity, Geography Compass, 1, 901-931, 10.1111/j.1749-8198.2007.00039.x, 2007.

Wang, X., and Melesse, A. M.: Effects of STATSGO and SSURGO as inputs in SWAT model's snowmelt simulation, J. Am. Water Resour. As., 42, 1217-1236, 10.1111/j.1752-1688.2006.tb05296.x, 2006.

Zhang, X. S., Srinivasan, R., Debele, B., and Hao, F. H.: Runoff simulation of the headwaters of the Yellow River using the SWAT model with three snowmelt algorithms, J. Am. Water Resour. As., 44, 48-61, 10.1111/j.1752-1688.2007.00137.x, 2008.

Zhang, Y., Chiew, F. H. S., Li, M., and Post, D.: Predicting Runoff Signatures Using Regression and Hydrological Modeling Approaches, Water Resour. Res., 54, 7859-7878, 10.1029/2018wr023325, 2018.

hat nach unten verschoben [8]: Viviroli, D., Mittelbach, H., Gurtz, J., and Weingartner, R.: Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results, J. Hydrol., 377, 208-225, http://dx.doi.org/10.1016/j.jhydrol.2009.08.022, 2009a.

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hat gelöscht: Viviroli, D., and Weingartner, R.: The hydrological significance of mountains: from regional to global scale, Hydrology and Earth System Sciences Discussions, 8, 1017-1030, 2004.

hat nach unten verschoben [8]: Viviroli, D., Mittelbach, H., Gurtz, J., and Weingartner, R.: Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results, J. Hydrol., 377, 208-225, http://dx.doi.org/10.1016/j.jhydrol.2009.08.022, 2009a.

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Table 2 The default and calibrated values of the most sensitive SWAT parameters

Parameter	Unit	Cal. Value	Default
SFTMP	°C	-0.5	1
SMTMP	°C	2.5	0.5
SMFMX	mm H_2O / °C day^{-1}	4.7	4.5
SMFMN	mm H_2O / °C day^{-1}	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
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 3 Absolute difference in days between simulated and observed values of the snowmelt timing, autumn recession period, peak flow timing and the centre of mass (COM), for the greater catchment feeding the Göscheneralpsee.

Year	Snowmelt timing	Autumn recession period	Peak flow timing	COM
1997	0	1	48	7
1998	2	1	2	4
1999	4	0	27	1
2000	0	16	19	3
2001	0	1	1	1
2002	0	19	0	8
2003	2	5	2	1
2004	1	4	21	2
2005	1	0	1	4
2006	3	1	3	4
2007	3	1	7	8
2008	2	0	2	3
2009	1	0	13	5

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2010	2	0	1	6
Average	1.4	3.5	11.0	4.0

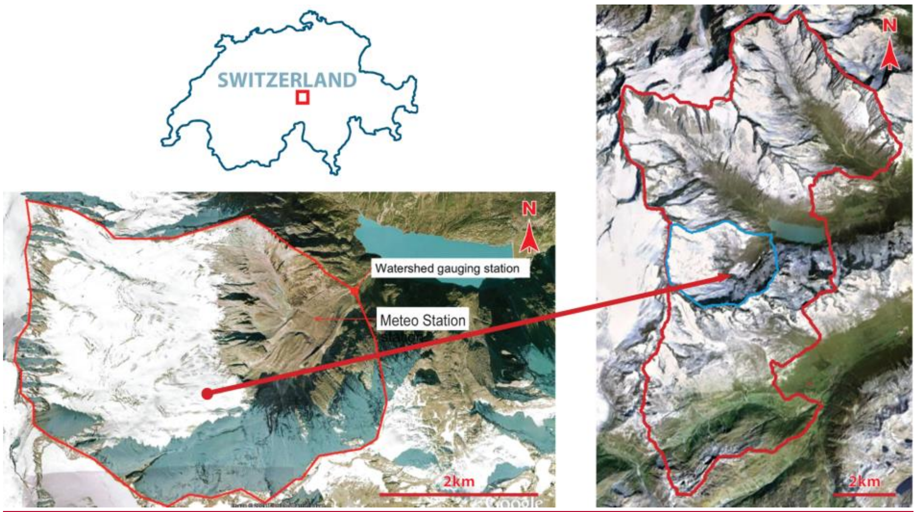
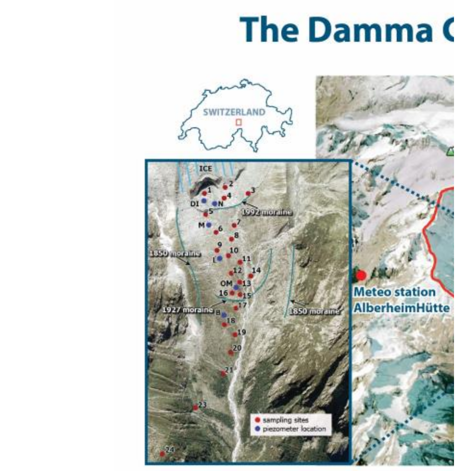


Figure 4 Map showing the Damma glacier watershed on the left and the greater area that feeds the Göscheneralpsee on the right.



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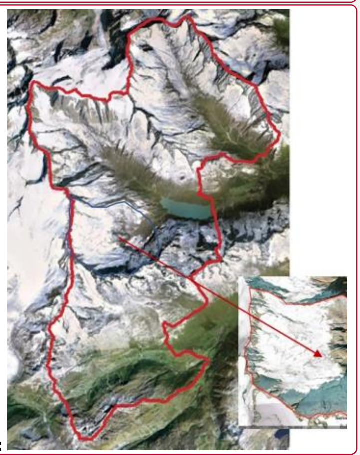

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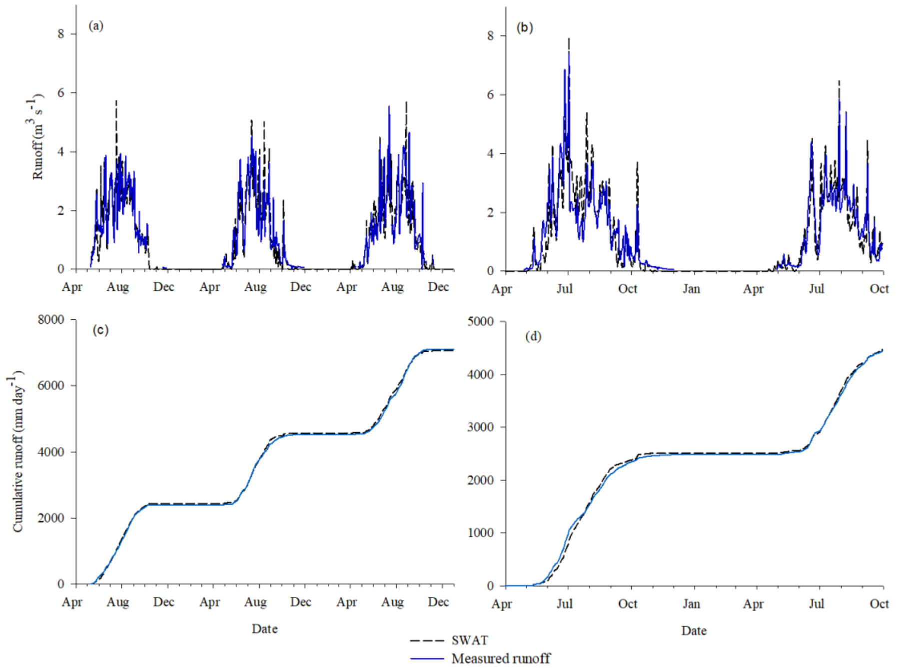

Figure 5 Observed and cumulative runoff for a) and c) the calibration period 2009-2011 and for b) and d) the validation period 2012-2013

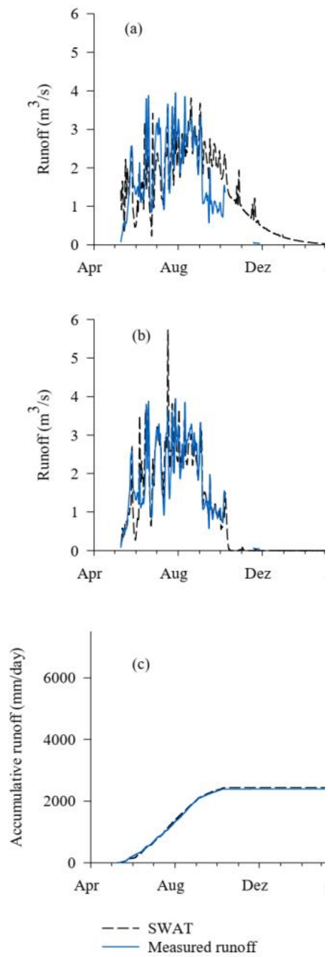

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Figure 3: Results from the calibration of SWAT model in comparison to the measured runoff of Damma watershed (a) before the calibration of the model and (b) after calibration. Graph (c) shows the simulated (after calibration) and measured accumulative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

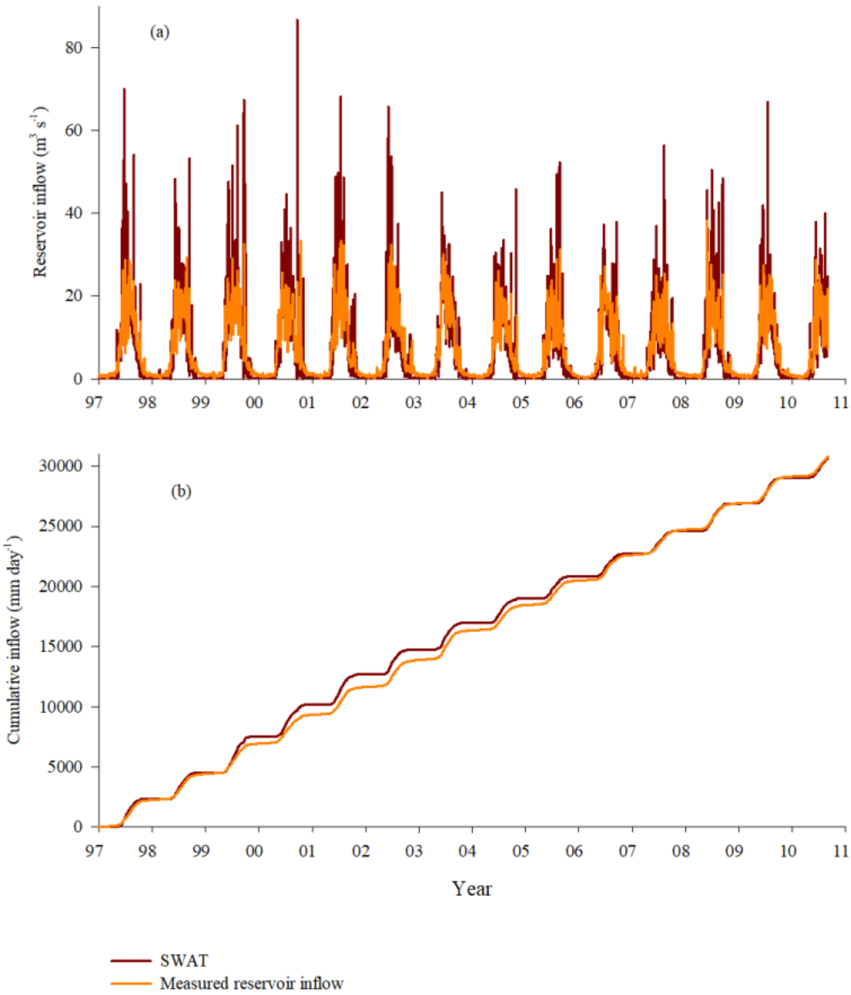
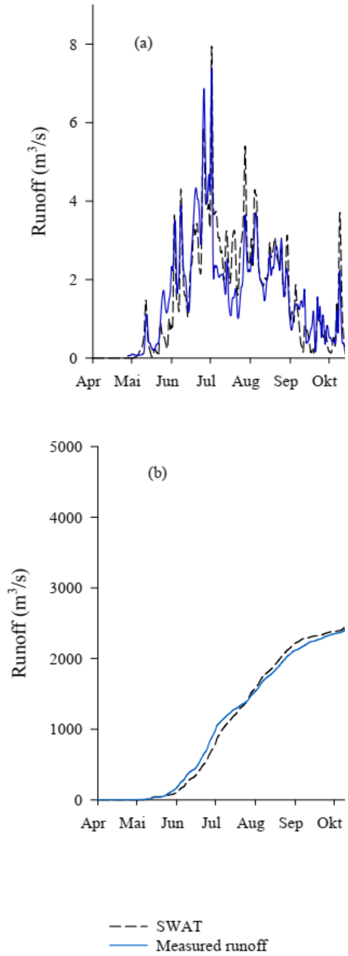


Figure 6 SWAT results and measured inflow of the feeding catchment of the Göscheneralpsee reservoir for the period 1997-2010. Graphs in (b) show the observed and simulated cumulative runoff over this period.



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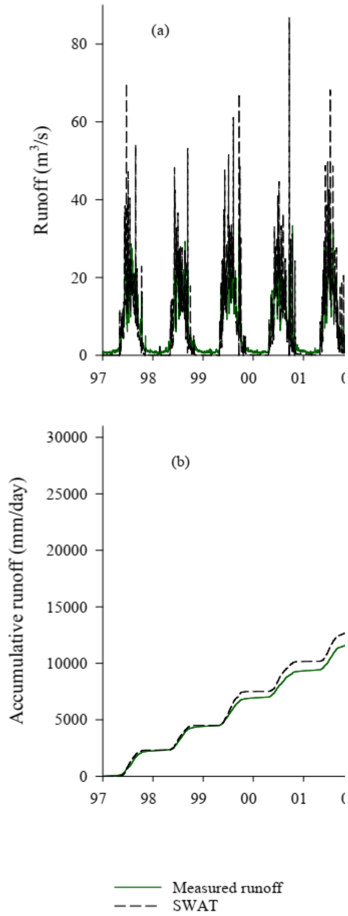

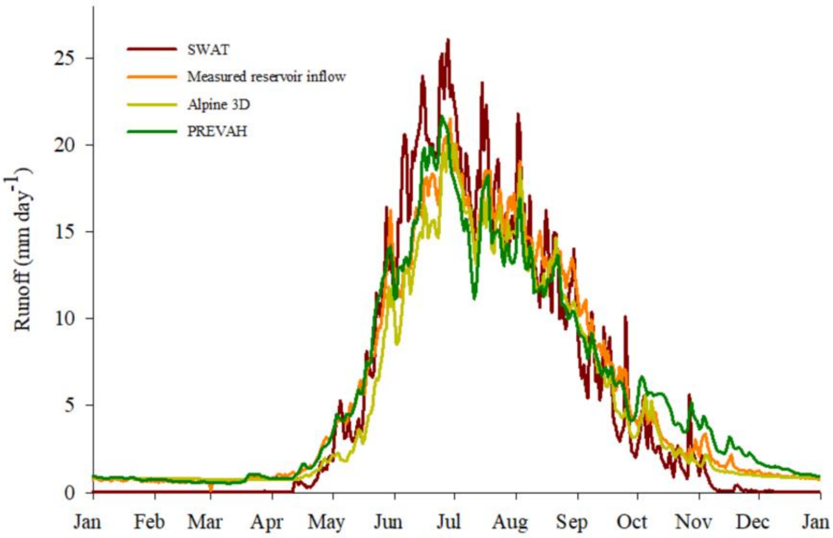

Figure 7 Interannual average of the results of SWAT, ALPINE3D and PREVAH models and the measured runoff of the Göscheneralpsee feeding catchment for the 1997-2010 period.

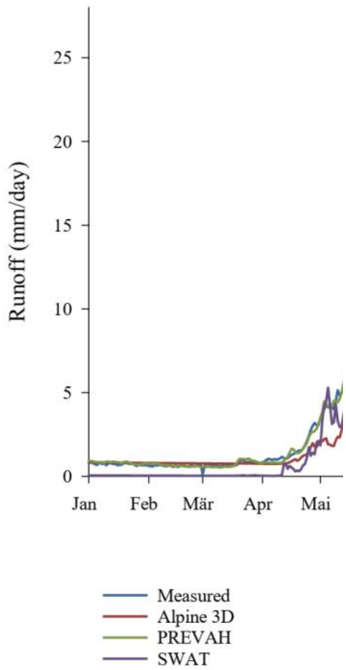

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Figure 6:

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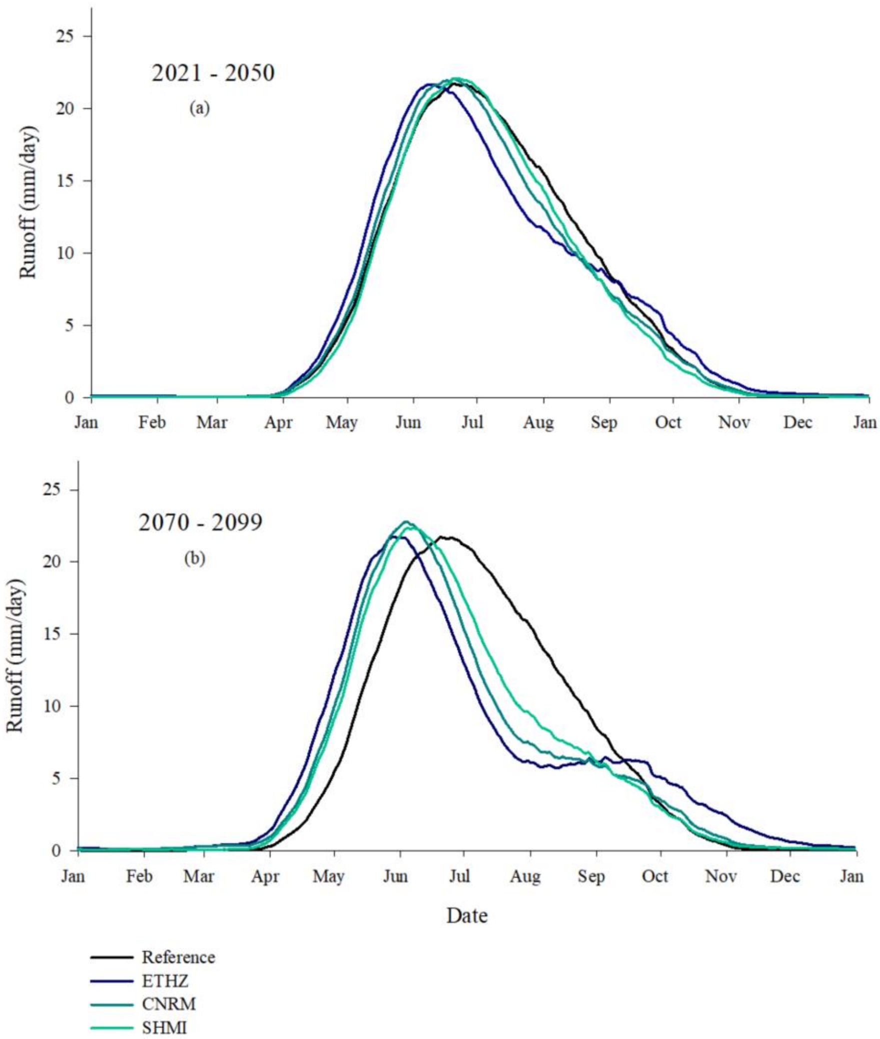
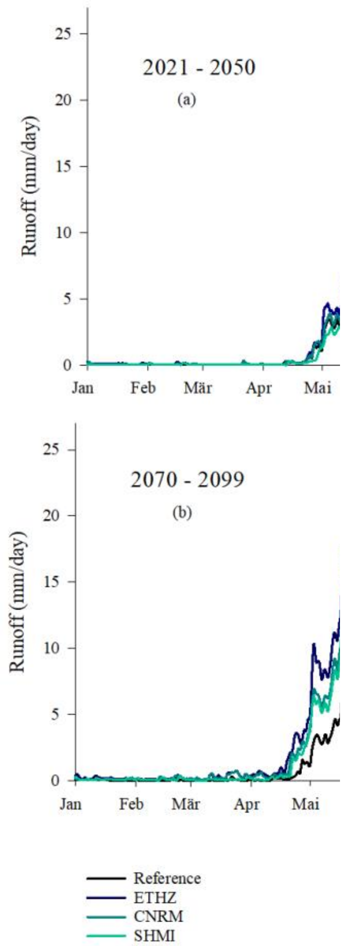


Figure 8. Interannual average of SWAT results of the three climate change scenarios and the reference period T0 for the Göscheneralpsee feeding catchment a) for the T1 period 2021-20150, and b) for the T2 period 2070-2099. A 30 day average window is applied.



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hat gelöscht: ¶
Figure 7:

hat gelöscht: future

hat gelöscht: for the reference and both future periods.¶

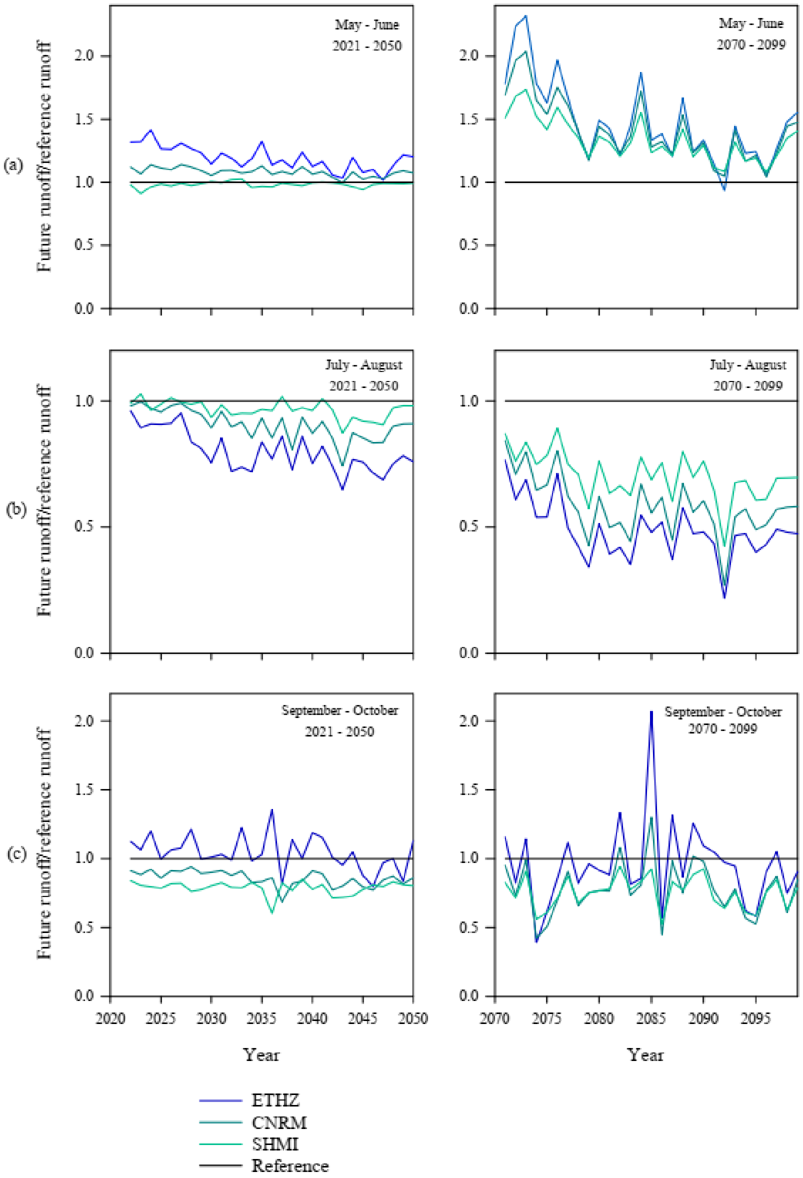

Figure 9 Seasonal changes of the simulated with SWAT runoff of the Göscheneralpsee feeding catchment for the reference T0 and future periods T1 and T2 for all three climate change scenarios. The interannual mean of the months a) May and June, b) July and August and c) September and October is taken.

hat gelöscht: ¶
Figure 8:

hat gelöscht: future

hat gelöscht: the

hat gelöscht: future