

# Cover Letter

hess-2012-232

## **Ice volume distribution and implications on runoff projections in a glacierized catchment**

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Dear Editor,

in the presented cover letter we discuss the corrections made in response to the suggestions of the two referees (Bettina Schäfli and Thomas Schuler) who reviewed the manuscript.

Emphasis has been set on clarifying the applied methodology, and on evaluating the uncertainties introduced by GPR measurements and the interpolation method.

In the following pages the comments by the referees are listed in bolds. The revised version of the text appears below in italics and smaller script size.

We are confident that the changes have resulted in an improved manuscript and acknowledge the reviewers for their helpful comments.

Kind regards.

Jeannette Gabbi

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## Answers to comments by reviewer 1 (Bettina Schäfli)

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Major comment 1:

**In its current form, the manuscript reads very well but it leaves me with the general impression that I do not really know what has been done in terms of modeling. All the modeling methods are presented elsewhere and reading this paper, I cannot judge how the results might be related to the modeling assumptions. In particular, there are almost no details on the hydrological model and its calibration (on very uncertain lake inflow data, see detailed comments), and the related glacier evolution model is, as far as I can see, not outlined (there is only a reference).**

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Our idea was to keep the methodical part of the article as short as possible in order to not extend the article unnecessarily. However, according to your and Thomas Schuler suggestions, we extended the methodical part and introduced additional explanations concerning the glacier evolution and runoff model, the generation of the climate time series, and the calibration procedure. For details on the changes done in the method section, see the answer to your first comment about paper structure/method.

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Major comment 2:

**Furthermore, the results are not compared to the results presented in (Schäfli et al, 2007b), which was a detailed study on the effect of climate change on the hydropower production system of Mauvoisin. Such a comparison (at least in a few words) seems important to assess the effect of scientific progress / additional information on the runoff projections: the study of Schäfli et al. made much more simplifying assumptions about the ice volume distribution (at a given moment in time, infinite ice volume for all catchment units covered by ice) and about the glacier evolution (glacier surface evolution with the so-called accumulation-area ratio, AAR). The infinite ice volume assumption would as such have been an interesting setting to test since this represents in fact the simplest assumption for studies that do not have any ice volume estimates (rather than your uniform assumption which still assumes knowledge of the total ice volume). And a comparison with the AAR method would be interesting because it is still widely used and this study presents a unique opportunity to show how this extremely simplifying assumption affects runoff projections.**

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According to your suggestion we added a comparison with Schäfli et al. (2007b).

Section 7 "Conclusion" (P7523):

*"Projections of the annual runoff volume and the runoff regime were compared to the results of the study by Schäfli et al. (2007) which investigates the influence of the climate change on the hydropower production in the Mauvoisin region by a more simplified approach. Our results show higher annual runoff volumes by the end of the 21<sup>st</sup> century compared to Schäfli et al. (2007). Changes in the daily runoff regime as a reduction of the peak discharge and the shift toward earlier in season are ascertained by both studies. However, a direct comparison is not possible, because (1) different climate scenarios were used, and (2) the investigated catchments differ in their extent."*

The goal of our study was to compare different ice volume distributions and to show the effect of the initial ice volume distribution on runoff projections. The focus of our sensitivity analyses was geared on more sophisticated approaches which consider an initial ice volume distribution and model the transient glacier evolution. The study of Huss et al. (2008) already compared the performance of the AAR method with the performance of the GERM model approach and showed that the performance of the AAR method is poor (annual runoff volumes are up to 30% lower and the glacierized area reduced by 30 to 55% by 2025 according to the AAR method). The AAR method does not fulfill the criterion of mass conservation and is therefore less realistic than a glacier evolution approach in combination with initial ice volume estimation (Huss et al., 2008). Hence, we think there is no need to show the performance of the AAR method again.

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However, in the Section “Discussion” a paragraph about the AAR method was added:

*“The simple approach to compute the glacier evolution is the Accumulation Area Ratio method (AAR) as used by several studies (e.g. Schäfli et al, 2005; Paul et al, 2007). This method updates the glacier surface according to the modeled accumulation area and a fixed accumulation area ratio assuming infinite ice volume. Moreover, no mass conservation is provided. Huss et al. (2008) showed a poor performance of the AAR method compared to an approach with a transient glacier evolution model and an initial ice volume distribution. According to Huss et al. (2008) the annual runoff volume are up to 30% underestimated by the AAR approach which is clearly below the performance of all tested ice volume distributions.”*

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Detailed comments:

Introduction

**I suggest removing references referring to studies in the tropical Andes and the Himalaya when talking about alpine systems; please refer to my paper (Schäfli et al, 2007b) rather than to my PhD thesis. Furthermore, I would not include references from before the 90ies as “in recent years”. Did Bergström study alpine basins? And Singh and Kumar? I suggest including (Horton et al, 2006) instead.**

We replaced the reference to the studies of Singh and Kumar, 1997 and Bergström, 1995 with references to studies about the Alps (Chen and Ohmura, 1990; Verbunt et al, 2003; Horton et al, 2006; Uhlmann et al, 2012) and cited your paper instead of your PhD thesis.

P7508 L20 – P7509 L5: “In many *high-mountain* basins the water supply to hydropower reservoirs primarily consists of snow and ice melt providing considerable amounts of water even in summer, when precipitation events are rare (Verbunt et al, 2003; Hock et al, 2005). Glaciers act as large freshwater reservoirs accumulating snow during the cold season and releasing the water accumulated as snow and ice during summer. This leads to sustainable differences in the runoff regime of glacierized basins compared to a non-glacierized ones (e.g. Chen and Ohmura, 1990). However, the projected climate change and the associated glacier retreat entail the potential risk of serious diminution of the glacial induced water supply (Braun et al, 2000; Huss et al, 2008; Farinotti et al, 2011). In recent years, different studies examined the impact of climate change on runoff projections for high-alpine basins (Braun et al, 2000; Verbunt et al, 2003; Horton et al, 2006; Schäfli et al, 2007; Huss et al, 2008; Farinotti et al, 2011; Uhlmann et al, 2012).”

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Case study

**The entire catchment connected to the accumulation lake of Mauvoisin has a size of 169 km<sup>2</sup> (Schäfli et al, 2007b). From Fig. 1 it is clear that you did not consider a part of the right hand side water intakes.**

We neglected the small catchment on the right hand side, because the runoff contributes only less to the total inflow to the runoff reservoir (8%) and because the remaining ice covered parts in this area are very small and consequently changes in their extent will hardly affect the entire stored water amount of the reservoir. However, for the generation of the runoff time serie of the natural catchment of the lake we considered the inflow of the pipeline on the right hand side of the lake. How the runoff time serie of the natural catchment of the lake was generated, is described in the last paragraph of Section 2 “Study site and data”. See also answer to the third comment to “Case study”.

**As far as I know, these water intakes do not have flow measurements, i.e. their contribution to the lake filling is included in the water level measurements. How did you subtract them?**

There are measurements of the water conducting line on the right and the left hand side. The water amounts of the pipelines were of course previously subtracted from the storage changes of the lake volume. Two “runoff” time series were generated, one for the natural catchment of the Mauvoisin lake and the other

for the additional catchment on the left hand side. The time serie for the natural catchment was derived by subtracting the water from the two additional catchments in the east and west and the amount of water used for generating electricity from the volume change of the reservoir.

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**Please mention explicitly that there are no runoff measurements, only indirect lake inflow estimations based on the lake outflow and lake level measurements (where the lake outflow is not observed directly but estimated from hydropower production, see the case study description in Schaefli et al, 2005 and Schaefli et al, 2007a).**

P7511 L1-5: *“Runoff data are available from the hydropower company Mauvoisin since 1982. The data includes water level variations of the Mauvoisin reservoir, its outflow and the input of the water conducting pipelines on the left and the right hand side (Fig. 1). [...] The runoff time serie of Mauvoisin catchment was generated by subtracting the inflow from the pipelines and the outflow of the reservoir from the lake level changes.”*

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**How did you handle the rather important uncertainties that arise for the estimation of lake inflow (e.g. negative inflow during the winter months, see Schaefli et al, 2007a)?**

Due to lack of knowledge how to solve this problem, negative inflow value during winter months were neglected. Since runoff data is only used for the runoff routing model and negative inflow values occur only in winter months when the runoff routing does not play a big role. We are confident that this source of uncertainties influence our runoff projections barely.

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**How did you calibrate your model on monthly data and a single year of daily data?**

We had daily runoff measurements at our disposal for more than one year. Daily runoff volumes exist for the period 2000-2009 and 2000-2005 for the Corbassière/Petit Combin catchment and the natural catchment of the lake, respectively. All model parameters except those describing the runoff routing were calibrated by other data sets than runoff measurements (mass balance measurements and ice volume changes). The runoff measurements were used only to adjust the parameters of the runoff routing model which was done manually. Model results were compared to the monthly and daily runoff data by comparing visually the two time series and by calculating the Nash-Sutcliffe criterion.

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Input data

**For what time periods did you have observed input data? Why did you not use the precipitation station of Mauvoisin?**

Temperature and precipitation time series were generated separately using different climate stations. For the generation of the precipitation time serie of the past the climate station Bourg-St-Pierre was used. The weather station Mauvoisin was neglected, because the time serie last only between 1992 and 2000 and particularly for the melt modeling it is more important to have long homogeneous records than a station close to the study site. Therefore, the weather station at Bourg-St-Pierre was chosen, which is in operation since 1900.

For temperature the climate station in Sion was used. The temperature lapse rate was computed by considering weather stations closer than 50 km to the study site, including the Mauvoisin station.

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Model calibration

**On which period did you calibrate, on which period did you validate your model?**

The model was cross validated for the two periods 1934-1983 and 1983-2009 given by the availability of the DEMs by means of observed ice volume changes and mass balance measurements. In a first step the model was calibrated for the period 1934-1983 and validated for the period 1983-2009 and vice-versa.

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Section 4.1.2 Calibration:

“The calibration of the model parameters was performed as described in Huss et al. (2008b) and Farinotti et al. (2012). In a first step, the parameters of the melt and the accumulation module are calibrated by means of observed ice volume changes and mass balance measurements (Huss et al., 2008b). *The parameters were cross validated by calibrating the parameters for the period 1934-1983 and validating them for the period 1983-2009 and vice versa.* In a second step, the parameters of the runoff routing model are adapted (Tab. 3).”

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**How can you give a range of Nash values for a single year of daily observations?**

The range of Nash values is a bit misleading. The two values are the results of the individual calibration of the two subcatchments: the natural catchment of the reservoir and the catchment on the left hand side. This partitioning was done due to the availability of the runoff data. As mentioned already in comment 5 of section “Case study” daily runoff measurements were available for more than one year.

To improve the clarity, we reformulated the sentence:

P7515 L2-4: *“The Nash-Sutcliffe criterion of the monthly runoff values is 0.93 and 0.94 for the Mauvoisin and the Corbassière and Petit Combin catchment, respectively, and of the daily runoff values 0.86 and 0.87, respectively.”*

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**A Nash-value of 0.79 is relatively poor for this type of runoff regimes (Schaepli and Gupta, 2007);**

According to the comment we had a closer look at the Nash-values. Unfortunately, the Nash-values for the daily runoff presented in the article are wrong, because for their calculation the whole period 1982-2009 was considered. But, daily runoff values are only available for the periods 2000-2005 and 2000-2009 for the natural and the Corbassière/Petit Combin catchment, respectively. This resulted in an underestimation of the correlation of daily runoff volumes. The new calculated Nash-values are 0.86 and 0.87 for the natural and the Corbassière/Petit Combin catchment, respectively. By applying a benchmark model (Nash values are calculated by comparing the observed daily time serie with daily values averaged over the whole period) Nash values of 0.77 and 0.84 are obtained for the natural and the Corbassière/Petit Combin catchment, respectively. These values are lower than the presented Nash values for the two catchments. Thus, the model performance is better than the simplified benchmark model.

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**Given that you analyze annual runoff volumes, it would be interesting to know the bias of the model.**

The bias of the model, i.e. the difference between the measured and modeled annual runoff is 1.2 mio m<sup>3</sup> of 205 mio m<sup>3</sup> (+0.6%) and -0.5 mio m<sup>3</sup> of 55 mio m<sup>3</sup> (-0.9%) for the natural catchment of the lake and the catchment on the left hand side, respectively.

Section Calibration (Page 7515, L5ff):

*“The bias between the modeled and the measured annual runoff is in average 1.2 mio m<sup>3</sup>a<sup>-1</sup> (+0.6%) and -0.5 mio m<sup>3</sup>a<sup>-1</sup> (-0.9%) for the Mauvoisin and the Corbassière and Petit Combin catchment, respectively.”*

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Paper structure/  
methods

**I think that there should be a methods section describing the basics of the used model to understand how it simulates glacier evolution and runoff and to have an overview of how many parameters have to be calibrated.**

We added short descriptions about each submodule of GERM in order to provide clarity (see also major comment 1). A table with the parameters of the melt,

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accumulation and runoff model was added.

P7513 L21ff: “For glacier and runoff projections the glacio-hydrological model GERM was applied (Huss et al, 2008; Farinotti et al, 2012). The model is fully distributed and consists of five different modules dealing with accumulation and ablation processes, glacier evolution, evaporation and runoff routing. Model and applications to alpine catchments are described by Huss et al. (2008) and Farinotti et al. (2012) in more detail.

The mass balance model is based on a temperature-index melt model according to the approach by Hock et al. (1999). It calculates the melt on a linear relationship between ablation and air temperature and includes the effect of potential solar radiation, thus accounting for the variability in slope, aspect and topographic shading. The local melt rate  $M$  is calculated in daily resolution by:

$$M = \begin{cases} (F_M + r_{\text{ice/snow}} * I) * T & : T > 0 \text{ } ^\circ\text{C} \\ 0 & : T \leq 0 \text{ } ^\circ\text{C} \end{cases}$$

where  $F_M$  is the melt factor,  $r_{\text{ice/snow}}$  the radiation factors for ice and snow, respectively, the potential solar radiation and  $T$  the mean daily air temperature. Below  $0^\circ\text{C}$  no melting occurs. The accumulation model interpolates the amount of precipitation at the reference location to any location in the catchment on the basis of a calibrated precipitation gradient  $dP/dz$  and a precipitation correction factor  $c_{\text{prec}}$ . A temperature range ( $0.5 - 2.5^\circ\text{C}$ ) distinguishes between snow and rainfall. Further, a spatial depending snow distribution factor accounts for snow transport processes through wind or gravity (e.g. avalanches).

Glacier surface is updated according to the so called dh-parameterisation (Huss et al, 2010). This method relies on the fact, that ice thickness changes across a longitudinal profile of a glacier show a typical pattern which is approximately constant over time (Johannesson et al, 1989). In the parameterisation, the annual ice volume change computed by the mass balance model is distributed over the glacier surface according to a predefined pattern. Thereby, the pattern is obtained analysing historic glacier changes in the region of interest.

The runoff routing model consists of three different reservoirs: an interception, a fast and a slow one. In first instance, the water infiltrates in the 'interception' reservoir until it is filled. Afterwards the water is distributed in the 'fast' and the 'slow' reservoir. The filling rate is thereby proportional to the actual filling level of the slow reservoir (Schäfli et al, 2005). The fast reservoir indicates the near-surface, fast responding runoff, the slow one the runoff from deeper layers retaining water over a longer period. In case of a snow cover there is a fourth 'snow reservoir'. The total runoff is computed by adding the discharge of the slow, the fast and the snow reservoir. The water loss of the interception reservoir is only controlled by evaporation. The individual reservoirs act as so called 'linear reservoirs' where the runoff volume is proportional to the actual filling level of the reservoir. The model distinguishes between five different surface types: ice, snow, rock, low (meadow), and high vegetation (forest). The size of the reservoirs and the corresponding retention constant are dependent on the surface type. For further details on the GERM model the reader is referred to (Farinotti et al, 2012).”

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**I also would like to have an idea how the meteorological variables were interpolated; furthermore it should be mentioned how results back to 1900 are obtained.**

For the temperature reconstruction back to 1900 we used the 12 homogenized weather stations of MeteoSwiss which provides monthly data since 1864. In order to receive daily temperature time series, daily temperature fluctuations of the weather station in Sion which reach back to 1900 were superimposed. For the precipitation time serie the weather station in Bourg-St-Pierre was used and the monthly means were scaled according to the PRISM data set.

P7514 L1-21: “The model is forced with continuous temperature and precipitation time series (1900-2100) with daily evolution. In order to reconstruct the past climate conditions

(1900-2009) in Mauvoisin area, regional temperature and precipitation data from weather stations in the vicinity of the study site are taken into account. Monthly temperature values between 1900 and 2009 were obtained by inverse-distance weighting of the homogenized climate time series of 12 different weather stations maintained by MeteoSwiss. In order to get temperature time series with daily resolution, daily fluctuations of the weather station in Sion were superimposed on the monthly values. Temperature lapse rates were computed by using data of weather stations closer than 50 km to the study area (Fig. 1). The homogenized temperature time series was shifted to the mean altitude of the investigated catchment by using the temperature lapse rate. For precipitation, the time series of the weather station of Bourg-St-Pierre was chosen due to the vicinity to the study site and the long record reaching back to 1900. Finally, this daily precipitation time series was scaled in order to match the monthly precipitation values given by the PRISM data set (Schwarb et al., 2001). The data set provides monthly precipitation sums for the Swiss Alps on a grid with 2 km resolution and the period 1971-1990. Precipitation lapse rate is determined during the calibration procedure by using the mass balance data. Temperature and precipitation lapse rate were kept constant over time. For further information about the generation of the climate time series of the past see Huss et al. (2008a)."

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**At the moment some methods are included in Section 4 that seems to be a mixture between methods and results.**

We tried to structure the paper in a different manner as usual in order to make a clear distinction between the three main parts of this paper. Hence, there is not the conventional structure of Data, Methods, Results, Discussion, and Conclusion. But a main part with three sections: 3. Ice-thickness distribution, 4. Glacier and runoff evolution and 5. Ice-thickness sensitivity analysis. Each section includes the specific methods and results. In order to provide more clarity we added some few words about the structure of the paper in the Introduction.

Introduction, last paragraph:

*"The main part of the paper is divided in three separate sections about (1) the ice thickness distribution, (2) the glacio-hydrological modeling, and (3) the ice volume sensitivity analysis whereby each section contains the corresponding methods and results."*

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**I also suggest to include some more text on the climate scenarios, mentioning at least some key numbers (future temperature, precip., spread between climate models).**

Following your suggestion we included additional information in the Section "Model forcing":

P7514 L11-21: "Future climate time series of the Mauvoisin region are based on scenarios developed in the framework of the European ENSEMBLES project (van der Linden and Mitchell, 2009). Regional climate scenarios of 10 different model chains (*combination between general circulation models and regional climate models*) based on emission scenario SRES A1B (IPCC, 2000) were used. The data were obtained from the Center for Climate Systems Modeling (C2SM) providing daily temperature and precipitation changes for two periods (2021-2050; 2070-2099) in the future in comparison to a period in the past (1980-2009) (CH2011, 2011; Bosshard et al., 2011).

In order to meet the model requirements of continuous climate time series the differences in temperature and precipitation between the different periods are linearly interpolated and an interannual variability based on the past is introduced. *We followed the approach of Farinotti et al., 2011 and generated for each model chain ten meteorological time series with a different day-to-day variability which results in 100 time series of mean daily temperature and precipitation."*

*"According the climate projections provided by the C2SM the temperature in the Mauvoisin region (weather station at 1840 m asl) will increase by about  $1.2^{\circ}\text{C} \pm 0.44$  on average until 2021-2050 and by about  $3.4^{\circ}\text{C} \pm 0.63$  until 2070-2099 compared to the reference period. Mean precipitation will increase by about  $1.4\% \pm 2.4$  until the first period, but decreases about by  $-2.8\% \pm 3.8$  until the second period. These average changes in temperature and*

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*precipitation are not uniformly distributed over the year. Temperature is projected to increase most during summer and precipitation most in spring and autumn."*

Paper structure/  
results

**I suggest moving Section 4.2 and 4.3 to a results section since otherwise it is not clear what is obtained from modeling and what from observation; this should be very clear (e.g. beginning section 4.3 discusses observed evolution; should this not be presented elsewhere?).**

Actually, Section 4.2 and 4.3 are in the result part of Section 4 "Glacier and runoff evolution". For better understanding, we divided section 4 in two parts: 4.1 Model and 4.2 Results with the subsections 4.2.1 "Glacier evolution" and 4.2.2 "Hydrology".

**All results discussing future evolution should explicitly refer to the future time period (e.g. for the uncertainty assessment on top of page 7522 it is not clear to what time period it refers).**

P7517 L 24-26: "In addition, snow melt peak is shifted from the beginning of July to the mid of May *until 2100* as a result of the earlier initiation of the snow melt season related to the warmer climate."

P7519 L10-12: In case of the GPR derived ice volume (1) annual runoff will slightly increase (about 4%) *between 2010 and about 2030* to a maximal annual runoff volume of 275 mio m<sup>3</sup> a<sup>-1</sup>.

P7519 L15-16: Peak discharge will occur around 10 years later with a volume of 279 mio. m<sup>3</sup> a<sup>-1</sup> (+1%) *compared to (1)*.

P7519/7520 L27/L1: But, in case (5) the annual runoff shows a sharper increase of 12% *between 2010 and 2040*.

P7522 L1-4: The study shows that a reduction of the temperature lapse rate by 10% yields a decrease of the mean annual runoff *between 2010 and 2100* of about 25% and that an increase of the melt parameters of 10% lead to an increase of the mean annual runoff of 11 to 20% *in the same period*.

P7522 L7-9: In case of the ITEM-derived glacier bed topography the total ice volume is overestimated by 36% leading to a reduction of the mean glacier-induced runoff *between 2010 and 2100* of about 31%.

PL7522 L9-11: This corresponds to a mean annual runoff reduction of about 4% *in the period 2010 to 2100*, what is less than the effect of the temperature gradient and the melt parameters, because the ice volume affects the ice melt component only.

**The discussion in 4.3 would benefit from a few references to existing study (since the main features of future runoff regimes are obtained in all similar studies).**

According to your suggestion, we included a small section with comparisons to similar studies:

P7516 L17: "*In comparison to a previous study addressing nine selected catchment in the Swiss Alps (Farinotti et al, 2012) the future runoff evolution in the Mauvoisin catchment shows a similar evolution as other strongly glacierized catchment.*"

P7517 L5: "*Similar changes in the runoff regimes of high-alpine basins in the future have been reported by other studies (Horton et al, 2006; Uhlmann et al, 2012).*"

Sensitivity  
analysis

**From Fig. 10, it appears that the moment of maximum annual runoff is almost linearly related to the initial ice volume estimate; what feature of the model / ice volume distribution leads to this result?**

The evolution of the annual runoff is controlled by the changes in the individual

runoff components. Changes in the snow melt do not influence the annual runoff, because for annual time scales it does not matter if the runoff originates from snow melt or liquid precipitation. In contrast, changes in glacier melt influence the evolution of the annual runoff. Hence, the time point of maximum annual runoff correlates with maximum glacier melt. As shown by the uniform ice volume distribution the moment of maximum annual runoff is not only related to the total initial ice volume, but also by its spatial distribution. However, the distribution of the ice thicknesses is the same in case (1), (2), and (3), and similar in case (5), and hence, in these cases the point of maximum annual runoff is related to the total initial ice volume.

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Discussion

**It seems like a uniform assumption is not too bad after all, especially if interested in long term projections; may be the sentence "A uniform ice volume distribution (..) is therefore for projections not suitable." is a bit too strong.**

You are right:

P7520 L12-14: *"A uniform ice volume distribution entails particularly in the next few decades an overestimation of runoff and is therefore less suitable for short- and mid-term projections."*

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**What is the order of magnitude of the uncertainty related to estimated area-average precipitation input?**

The uncertainty related to the estimated area-average precipitation input is difficult to estimate, because only few direct measurement exist which are not representative for the whole catchment. Furthermore, the accuracy of those precipitation measurements is difficult to assess due to gauge undercatch errors. For these reasons no value can be assigned to this source of error.

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**Are you confident that your calibrated model is suited to simulate future runoff?**

The used model is based on a statistical relationship between melt and mean daily temperature (temperature-index melt model). The model was calibrated over a long period (1934 to 2009) and an average parameter set was used for the future which provides a solid basis for projections. We can not exclude that in future the glaciers will behave differently for example due to changes in the solar radiation or changes in the albedo of the glacier surface. Due to lack of knowledge about those processes, it is not possible to include them in the model. Thus, the model is an appropriate approach for generating glacier and runoff projections for glacierized catchments as far as currently known.

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**Table 3 indicates that in the future, up to 25% of the non-glacierized runoff is surface runoff. What explains this?**

Due to the strong retreat of the glaciers and the warming less snow and glacier runoff is expected by end of the 21<sup>st</sup> century. Hence, the fraction of runoff from other reservoirs (surface and subsurface) will contribute stronger to the total runoff. The runoff from the surface will increase more than runoff from the subsurface, because areas of the catchment becoming recently ice free have a lower capacity of storing water in the subsurface. Thus, a stronger increase in the surface runoff compared to the runoff from the subsurface is expected.

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Conclusion

**For my taste, the conclusion is too strongly focused on the now well known effect of climate warming on runoff, which was not the main focus of the study; it is in exchange, not stressed how important good ice volume estimates might be for projections for the next 30 years or so; and no outlook is given on how such good estimates might be obtained.**

We improved the conclusion according to your suggestion and put the focus more on the ice-thickness sensitivity analysis than on the runoff projections:

P7523 L6-23: *"In this study we combined results from extensive GPR measurements with an ice thickness estimation approach (Farinotti et al, 2009), for determining the present ice volume in the Mauvoisin area. A total ice volume of 3.69 0.31 km<sup>3</sup> was calculated by including all available measurements and a maximal ice-thickness of 291m was found. The derived ice volume distribution served as input for a combined glacio-hydrological model (Huss et al, 2008; Farinotti et al, 2011), by which glacier and runoff projections were determined. By means of a sensitivity analysis we could demonstrate that an under- or overestimation of the total ice volume may lead to severe distortions of the runoff projections and potentially even to deviations from the projected general runoff trend. Particularly for projections for the next 20 to 30 years an accurate ice volume determination and an appropriate ice-thickness distribution is crucial. The study emphasizes the importance of the incorporation or GPR measurements in order to get reliable ice thickness distributions. Including ice-thickness measurements clearly increases the accuracy of the ice volume estimation and hence, the runoff projections.*

According to our model the annual runoff will rise about 4% to a maximum of 275 mio m<sup>3</sup>a<sup>-1</sup> until around 2030 and will drop in the subsequent period to 207 mio m<sup>3</sup>a<sup>-1</sup> by 2100. The runoff regime is expected to change from an ice-melt to a snow-melt dominated regime. Maximum mean daily runoff will decrease from 28 m<sup>3</sup>s<sup>-1</sup> to 18 m<sup>3</sup>s<sup>-1</sup> from 2010 to 2100 and will occur one and a half month earlier by 2100 than in the reference period."

Table 3

**Does the indicated year correspond to the end of the 30 year period? It is clear from the numbers that the annual runoff corresponds to the sum of the other components.**

The values correspond to the mean of the  $\pm 5$  years from the indicated year.

Caption Table 3: "Summary of the main results of this study. The evolution of the ice volume, the glacierized area, the annual runoff and the different runoff components (ice melt, snow melt, runoff from non-glacierized area and runoff from the subsurface) is shown for the period 1920-2100 in 30-years steps. *Values are averaged over  $\pm 5$  years.*"

**The naming of these components is a bit misleading since for the glacier part, the naming refers to the input type (melting ice or melting snow), whereas for the non-glacier part, the naming refers to the flow path. There is certainly snow runoff from the non-glacierized catchment parts, would it not be interesting to know its evolution, even if it is not the focus of the paper? Furthermore, "Q non-glacierized" should probably be relabeled since it is only surface runoff.**

According to the comment, we reanalyzed our runoff components and came to the conclusion that they are not easy to understand. For these reason we decided to generate a new figure which is clearer. The revised figure shows the different components of the water input in the runoff routing model considering pure ice melt, snow melt and liquid precipitation. Firn melt is assigned to the ice melt. The new figure is more helpful to understand the changes in the runoff regime, because the origin of the components is clearer. But, it must be kept in mind that the sum of these three components do not correspond exactly to daily runoff volumes, because runoff routing is not considered.

According to this revised figure also the paragraph about the runoff components in Section 4.2.2 "Hydrology" and Table 5 were updated.

Section 4.2.2 "Hydrology":

*"The reason for these changes in the runoff regime becomes evident by considering the evolution of the different sources of the water input to the runoff model with progressing climate change (Fig. 8). The model employed distinguishes between: liquid precipitation, snow melt, and ice melt. Firn is counted to ice melt. Between the sum of the three water input components (Fig. 9) and the runoff regime (Fig. 8) is a slight difference originating from*

runoff routing. During the reference period (1980-2009), snow melt is the main component and account for 60% of the water input. At present, snow runoff contribution starts to increase mid of May and reaches a maximum at the beginning of July. The ice melt increases later in the season (at the beginning of June) and its maximum occurs around the end of July. Model projections show that maximum snow melt is shifted to the beginning of June and that the ice melt is reduced and its maximum shifted to mid of August by the end of the 21<sup>st</sup> century. Hence, the shift of the snow melt peak and the reduction in ice melt leads to reduced runoff volumes in July and August as shown by the runoff regime evolution.

According to our model ice melt will decrease about 74% between 2010 and 2100 and will contribute only by 2% to total runoff in the year 2100. The remaining runoff originates in equal parts from snow melt (48%) and liquid precipitation (50%). Snow melt will experience a less pronounced decrease than ice melt. From 2010 to 2100 snow melt reduces about 11%. The reason for the reduction of snow melt is caused by less solid precipitation due to the expected temperature rise and by generally decreased precipitation. In fact, total precipitation will reduce about 6% until 2100 compared to the reference period (1980-2009). The results of the runoff analysis are summarized in Table 5."

---

Figure 4

**I suggest to add uncertainty bands also to the observed ice volume evolution; also, it is not clear from the text, what explains the uncertainty bands of the projections. To my view, there is not enough information about the climate scenarios to understand this spread.**

According to the comment, we included uncertainty bands to the observed ice volume estimation in Figure 5. Further, we added additional explanations about the climate projections in Section 4.1.1 "Model forcing" and in the caption of Figure 5 itself in order to make it clearer from where the uncertainty bands of the projections arises. For further information about the changes see also answer to comment about P7514 of Thomas Schuler.

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Figure 6

**It would be interesting to add "plausibility" intervals to the runoff simulated for the past; these bands could account for the sources of uncertainty quantified in the text; not quantified are parameter uncertainty and area-average precipitation uncertainty.**

According to the suggestion we added uncertainty bands to the Figure 7. They were calculated according to the bias between modeled and measured annual runoff. The uncertainty of the used parameters is difficult to quantify. In order to ensure the validity of the used parameters, the calibration was performed over an extended period of time (1934-2009). For area-average precipitation uncertainty see answer to second comment of the section Discussion.

---

Figure 7

**The subsurface component of the runoff should be relabeled, it is not groundwater; I suggest relabeling all of the runoff components; from this figure, I conclude that  $Q_{\text{snow}}$  also contains snow-induced runoff from the non-glacier covered catchment part (given that the contribution of the glacier-free part starts so late in the year); please clarify.**

See answer to the second comment to Table 3.

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## Answers to comments by reviewer 2 (Thomas Schuler)

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Major comments:

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Major comment 1:

**“In general, the MS provides very little information on GPR data and the associated uncertainties although these data are the backbone for the analysis presented here.”**

We included a new section about "Uncertainties of GPR data" subsequently to the Section "GPR Processing" which discusses all potential sources of errors and added a comparison between ground-based and helicopter-based GPR measurements. Furthermore, a figure which shows the differences between the two measuring techniques is added.

### 3.1.2 Uncertainties GPR measurements

*“Uncertainties of the ice thickness measurements origin from different sources of error. The main uncertainty arises due to blurry reflection horizons. Always the upper boundary of the reflection band was picked. By the identification of the bed reflections, care was taken to ensure that no sharp edges of the bed topography result. The uncertainty of this source of error can be assigned to  $\pm 5\text{m}$  on average. In isolated areas uncertainties of up to  $\pm 15\text{m}$  can occur due to blurry reflection. Another source of error are uncertainties about the propagation velocity of the electromagnetic wave. The velocity is well known and therefore the effect on the uncertainty of the ice thickness measurements is negligible small. Further uncertainties are introduced by the projection of the GPR signals on a two dimensional profile section. The uncertainties associated with this kind of error are spatial highly variable and are difficult to quantify. Hence, this error was not included in the uncertainty analysis. According to these considerations an overall uncertainty of  $\pm 5\text{m}$  was determined for the GPR measurements.*

*In order to verify the accuracy of the GPR signals, a comparison between ground- and helicopter-based GPR measurements was performed. The helicopter-based GPR measurements were arranged in a manner allowing a comparison to ground-based measurements. As shown by Figure 4 the ground-based agree well with helicopter-based GPR measurements. Remaining differences of the ice thicknesses are mainly due to slight deviations in the projections of the GPR profiles.”*

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Major comment 2:

**“For instance, the blurr of the bottom reflection in Fig2 indicates that uncertainties related to locating the reflector may be considerable.”**

We added the image in higher resolution in order to improve the visibility of the reflection. For further information about the uncertainties of the GPR profiles see answer to major comment 1”.

---

Major comment 3:

**“Also, as indicated in Fig3, some airborne GPR profiles have been ground-truthed. What were the results of the comparison?”**

The helicopter-based radar profiles were arranged in such a way that they coincide with the ground-based radar profiles in order to allow a comparison between these two types of GPR profiles. A comparison was done but for reason of space not shown in the paper. According to your suggestion, we implemented a figure (Figure 4) and added a few words about the results of the comparison in the Section about the uncertainties of GPR profiles. See answer to major comment 1.

---

Major comment 4:

**“Further, I am missing an analysis of how the uncertainties of the measurements and those of the interpolation method affect the final ice volume and the related runoff evolution.”**

We added a paragraph about the uncertainties of the interpolation method in Section 3.2 “Ice-thickness measurements” and discuss the effect of the uncertainty of the ice volume on runoff projections in the Discussion section. For information about the uncertainties of the GPR measurements see answer to major comment 1.

---

Section 3.2 “Ice-thickness estimation”:

*“By interpolation of the GPR profiles uncertainties are introduced in the ice volume estimation. In order to determine the magnitude of this kind of error the ice thickness estimation model was run multiple times for a different number of GPR profiles. By each model run a GPR profile was added to the set of ice thickness measurements leading to a continuous increase in the accuracy of the ice volume estimation. By including the last profiles to the interpolation, the ice volume approached to a level of about 1%. Hence, the uncertainty introduced by the interpolation method is small for glaciers with a comprehensive set of ice thickness measurements. The uncertainty of the ice volume calculation of glaciers without ice thickness measurements was assessed taking the performance of the uncalibrated ITEM parameters into account. Uncertainties of the ice volume calculation are shown in Table 4.”*

Section 6 “Discussion”:

*“Despite the high density of ice-thickness measurements and the application of an ice thickness estimation method, the true bed topography is not fully known. Uncertainties arise due to uncertainties of the ice thickness measurements and the interpolation method. Taking these two sources of uncertainties into account, an overall uncertainty of  $\pm 8\%$  was determined for the ice volume. This uncertainty leads to the same deviations in the runoff projection as shown by the results of the sensitivity analysis for under- and overestimated ice volumes (20%), but less pronounced.”*

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Major comment 5:

**“The MS explores only the differences between the interpolation methods, but not the implications of uncertainties inherent even in the best interpolation scheme. However, this is something that I expected from the title of the MS.”**

See answer to major comment 4.

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Major comment 6:

**“As mentioned above, the MS in its current state is not self-contained. Sec 4 provides too little information on the methodology applied (GERM, delta-h approach etc). Although GERM and the delta-h approach are established methods (and referenced), self-containment requires adding a few more lines describing the principles behind, the assumptions involved and the parameters to be determined. This is particularly needed for Sec4 where sec 4.1 describes the methodology, but sec4.2 ff dives directly into the results.”**

See response to the first comment about “paper structure/methods” of the first reviewer (Bettina Schäfli).

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Major comment 7:

**“Description of results should use more careful wording, acknowledging that these are model results but not the definite truth. For instance, on P7516, L18ff: ‘The changing climate. . .will affect. . .’ could be put into perspective by adding an ‘According to our model. . .’”**

---

We tried to take more care about the wording and reformulated several sentences of the result part of the paper.

P7515 L14/15: *“According to the applied model, all glaciers in the Mauvoisin region will severely retreat in the future independent of their size.”*

P7515 L19-21: *“Small glaciers or parts of them below 3000 m a.s.l. are expected to disappear by 2020 as in the case of Glacier de Fenêtre, Glacier de la Tsessette and, to some extent, also Glacier de Crête Sèche.”*

P7515 L23/24: *“Model results revealed that larger glaciers, especially those with large ice volumes and high-altitude accumulation areas, will retreat considerably slower than the smaller ones.”*

P7515 L26-28: *“Glacier d'Otemma shows a particularly fast retreat in contrast to the other larger glaciers in the area as indicated by our model.”*

P7516 L7/8: *“According to our reconstruction the annual runoff increased from 216 to 265 mio m<sup>3</sup>a<sup>-1</sup> (23%)”*

between 1900 and 2009, but this rise was not constant over time.”

P7516 L13/14: “In the next two decades, annual runoff is *projected to* increase to approximately 275 mio m<sup>3</sup> a<sup>-1</sup> (+4%).”

P7516 L21-23: “*Modelled runoff projections indicate that* in future, the mean daily runoff in summer will strongly diminish, whereas during winter daily runoff will slightly enhance due to higher air temperatures.”

P7516 L26/27: “*According to the model* maximal runoff values will occur one-and-a-half months earlier at the end of the 21<sup>st</sup> compared to the reference period.”

P7517 L1-3: “Furthermore, *the runoff projections indicate* that the daily runoff increase slightly earlier in spring compared to the present situation due to the earlier onset of the snow melt season.”

P7518 L18ff: “*According to our model* the annual runoff will rise about 4% to a maximum of 275 mio m<sup>3</sup> a<sup>-1</sup> until around 2030 and will drop in the subsequent period to 207 mio m<sup>3</sup> a<sup>-1</sup> by 2100.”

---

Minor comments:

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P7508 L13 **'...that reliable estimates ARE essential', essential for what?**

“Our analyses revealed that reliable estimates of the ice volume *are essential for modelling future glacier and runoff evolution.*”

---

P7509 L15 **...'runoff projections', state the timescale of the projections (e.g. until 2100)**

“This study focuses on the determination of the glacier bed topography in the Mauvoisin region and the impact of the initial ice volume distribution on runoff projections of high-mountainous catchments *until 2100.*”

---

P7509 L20ff **References to 'Chapter 3' etc...a paper is not subdivided in chapters but sections**

Ok!

---

P7509 L26 **'the impact of inaccurate estimations...' all presented estimates are inaccurate better talk about 'uncertainty' associated with each method.**

“In the scope of this study, the impact of *uncertain* ice-thickness estimations, due to a lack of ice-thickness measurements or the use of inappropriate ice-thickness estimation methods, on runoff projections was analysed (Section 5).”

---

P7510 L8 **It is inconsistent to present the result of your ice volume estimation in the site description. This belongs to sec3!**

Ok!

---

P7510 L13 **'the local climate' apparently refers to a given location in your domain and should be identified**

“The *climate in the Mauvoisin region* is characterized by mean precipitation amounts of about 1600 mm a<sup>-1</sup> and a mean annual temperature of -3.5°C.”

---

P7510 L27 **'More details ...are shown in Table 2.' WRONG: Table 2 does not provide more details.**

*"An overview on the used data sets is shown in Table 2."*

---

P7511 L2 **'...since...the 1980s' -> since 1982**

*"Runoff data are available from the hydropower company Mauvoisin since 1982."*

---

P7511 L3 **The 'water conducting line' should be specified in Fig 1.**

It is specified in Fig. 1!

---

P7511 L3/4 **'Runoff measurements...' ...is actually incorrect. Discharge is not measured but inferred from water level records etc.**

We corrected the inappropriate term and replaced it with "inflow and lake level measurements".

*"Runoff data are available from the hydropower company Mauvoisin since 1982. The data includes water level variations of the Mauvoisin reservoir and the input of the water conducting pipelines on the left and the right hand side (Fig. 1). Inflow and lake level measurements have monthly resolution for the period 1982 to 2000 and daily resolution since 2000."*

Further, we implemented a sentence about how the runoff time series were generated in order to avoid confusion.

L 10ff: *"The runoff time serie of Mauvoisin catchment was generated by subtracting the inflow from the two pipelines and the outflow of the reservoir from the lake level changes."*

---

P7511 L13 **'...significant bedrock reflections' ->clearly detectable reflections**

*"122 km of GPR profiles were recorded whereof 55 % showed clearly detectable reflections, such that they could be incorporated in the ice volume calculation."*

---

P7511 L19 **Reference to Fig 3 before Fig 2 is referenced -> change sequence of the figures?**

Ok!

---

P7511 L23 **...'straight profile ...'this sentence is difficult to understand. Was the GPR record not tied to a GPS record?**

The GPR record was tied to a GPS record. But, according to the gated stepped mode of the acquisition technique several traces with different frequencies of the electromagnetic wave were recorded which do not coincide exactly at the same location. For this reason the individual GPR signals were projected on a straight profile.

*"In a first step, the positions of the GPR signals of the different traces were projected on straight profiles which is required for the further processing of the GPR data."*

---

P7511 L24 **'spatial filters' .why spatial?...do you mean special filters?**

---

'Spatial filters' is correct, but a better term is 'multichannel filter'. We reformulated this sentence to make it clearer.

*"In order to remove the inherent system ringing of GPR acquisition systems a singular value decomposition based on multichannel filters has been applied."*

---

P7512 L10-13 **I do not agree in that the 'reflection is clearly visible' in Fig2, instead it appears blurry.**

The bed topography is despite blurry sections along the profile clearly visible. We added Figure 2 in higher resolution in order to make reflection horizon more evident. See also answers to major comment 1 & 2.

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P7512 L16 **'the literature DESCRIBES different...'**

*"The literature describes different ice-thickness estimation approaches of various complexity..."*

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P7512 L20 **'...we APPLIED the Ice-Thickness Estimation Method..'**

*"In this study we applied the Ice-Thickness Estimation Method (ITEM) of Farinotti et al, (2009b)."*

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P7512 L24/25 **'The ice flow is converted into ice thickness' sound more magic than scientific, consider: 'Ice thickness is derived from inverting Glen's flow law..'**

*"The ice thickness is derived from inverting Glen's flow law (Glen, 1955)."*

---

P7512 L26 **'This factor has to be calibrated..' How? To conserve the cross sectional area occupied by ice, or to conserve maximum ice thickness, or.? there are many possibilities, please provide more detail here.**

The c-factor was calibrated in order to maximize the agreement between GPR measurements and calculated bedrock. The calibration is performed for each available GPR profile individually. Between individual profiles the factor is interpolated linearly. For glacier without profiles, a mean value of c is used.

We added a short comment in the corresponding section:

*"This factor has to be calibrated by ice-thickness measurements in order to maximize agreement between GPR measurements and calculated bedrock or has to be estimated from other glaciers."*

---

P7513 L1 **'We have USED our...TO identify..'**

*"We have used our GPR measurements to identify suitable correction factors for each profile."*

---

P7513 L1 **Stick to a consistent terminology: use either 'calibration factor' or 'correction factor', not both.**

Ok! Correction factor is the correct term.

*"We have considered our GPR measurements for identifying suitable correction factors for each profile. ..."*

---

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P7513 L5 **Reference to Table 4 before Table 3 is referenced -> change order of Tables according to the sequence how they are referred to in the text.**

Ok!

---

P7513 L8 **Reference to Fig3: fig3 doesn't show volumes, better refer to Tab 4.**

Ok!

---

P7513 L18 **remove 'only' (subjective rating)**

"In comparison, Glacier du Mont Durand shows a lower maximal ice-thickness of 144 m."

---

P7513 L24/25 **'...applications TO...are described BY...'**

"Model and applications *to* alpine catchments are described *by* Huss et al. (2008) and Farinotti et al. (2012)."

---

P7513 L24/25 **Here, it would be helpful to know more about the model: the principles behind, the assumptions involved and the parameters used. A table presenting the values of the calibrated and preset parameters is necessary to fully evaluate the model performance. Here, the authors have made assumptions on the relationship between meteorological variables and glacier mass balance, on the response of glacier geometry to changes in mass balance and on the generation of runoff.**

Our idea was to keep the part about the model description short, because it was used in several studies and is well described in the papers of Huss et al., 2008 and Farinotti et al., 2012. But, we agree that it could be helpful for those who are not familiar with the model if we include some more basic information about the model. In order to give an overview on the parameter used, we added Table 3. See response to first comment about "paper structure/method" of reviewer 1 (Bettina Schäfli).

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P7514 **Description of model forcing: please state the spatial resolution of the domain and the modeling time step. From the context it becomes clear that the model was applied to a historical period 1900-2009 and a projection from 20XX -2100, this should be clearly indicated here.**

We added comments about the time step in the Section 4.1.1 "Model forcing" and included information about the model resolution and the time span for which the model was run in the first part of the Section 4.1 "Glacio-hydrological model".

7514: "The model is forced with continuous temperature and precipitation time series (1900-2100) with daily resolution. In order to reconstruct the past climate conditions (1900-2009) in the Mauvoisin area, regional temperature and precipitation data from weather stations in the vicinity of the study site are taken into account. [...] Future climate time series (2010-2100) of the Mauvoisin region are based on scenarios developed in the framework of the European ENSEMBLES project (Van der Linden & Mitchell, 2009)."

7513 L24ff: "For glacier and runoff projections the glacio-hydrological model GERM was applied (Huss et al., 2008; Farinotti et al., 2012). The model is fully distributed and consists of five different modules dealing with accumulation and ablation processes, glacier evolution, evaporation and runoff routing. *The model was run on a daily basis for the time period 1900 to 2100 with a spatial resolution of 50 m and 25 m for the Mauvoisin and the Corbassière/Petit*

*Combin catchment, respectively. Model and applications to alpine catchments are described by Huss et al, 2008 and Farinotti et al, 2012.”*

---

P7514 L7 **Concerning lapse rates: what is the temporal resolution of lapse rates? Same as model time step, seasonal or a constant? Provide more detail.**

The lapse rates were kept constant over time. This information was added.

Temperature lapse rates were computed by using data of weather stations closer than 50 km to the study area (Fig. 1). *The homogenized temperature time serie was shifted to the mean altitude of the investigated catchment by using the temperature lapse rate. [...]Precipitation lapse rate is determined during the calibration procedure by using the mass balance data. Temperature and precipitation lapse rate were kept constant over time.*

---

P7514 L8ff **‘precipitation time series . . .are computed. . .’ how? Provide more detail**

In order to provide more clarity we added further explanations about the generation of the temperature and precipitation time series:

*“Monthly temperature values between 1900 and 2009 were obtained by inverse-distance weighting of the homogenized climate time series of 12 different weather stations maintained by MeteoSwiss. In order to get temperature time serie with daily resolution, daily fluctuations of the weather station in Sion were superimposed on the monthly values. Temperature lapse rates were computed by using data of weather stations closer than 50 km to the study area (Fig. 1). The homogenized temperature time serie was shifted to the mean altitude of the investigated catchment by using the temperature lapse rate. For precipitation, the time serie of the weather station of Bourg-St-Pierre was chosen due to the vicinity to the study site and the long record reaching back to 1900. Finally, this daily precipitation time serie was scaled in order to match the monthly precipitation values given by the PRISM data set (Schwarb et al, 2001). The data set provides monthly precipitation sums for the Swiss Alps on a grid with 2 km resolution and the period 1971-1990. For further information about the generation of the climate time serie of the past see Huss et al, 2008a.”*

---

P7514 L18ff **This sentence is hard to grasp. Add more information on this procedure.**

We reformulated this paragraph and added some further information of the procedure used to generate future climate time series.

*“In order to meet the model requirements of continuous climate time series the changes in temperature and precipitation between the three periods are assigned to the middle of each period and are linearly interpolated inbetween. An interannual variability is introduced by superimposing daily fluctuation of the past on the interpolated time series. We followed the approach of Farinotti et al (2012) and generated ten different meteorological time series for each of the ten considered model chains. This results in 100 different time series of daily temperature and precipitation by which the model can be forced and allows to estimate a possible bandwidth for the climate evolution.”*

---

P7514 L21 **‘100 different time series’. explain your motivation for doing so and provide more information on the procedure. Did you conduct 100 realisations of the model using the different series as input? The mean/median of the ensemble of results is then considered as the most likely situation for the projection?**

As described in the paper we used results from 10 different model chains (different combinations of global circulation models and regional climate models) of the ENSEMBLES project. The Center for Climate Systems Modeling (C2SM) provided us with the data in terms of changes of temperature and precipitation between a reference period in the past (1980-2009) and two periods in the future (2021-2050;

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2070-2099) for each model chain. Hence, for each model chain daily temperature and precipitation changes between the reference period and the first period in the future and between the reference period and the second period in the future are provided. These changes in temperature and precipitation were assigned to the middle of each period and were linearly interpolated between the periods. In order to introduce a day-to-day variability a year of the past is chosen randomly and its daily fluctuations applied to the linearly interpolated time series. This was done 10 times for each model chain in order to provide a certain 'bandwidth' for the climate evolution. The glacier evolution and runoff model was then forced by this 100 climate time series whereby the median and the 95% confidence interval of the 100 different realizations are indicated in the figures.

We implemented some further explanation about the generation of the climate time series in the future to provide more clarity (see answer to comment P7514 L18ff).

---

P7515 L1-5 **Again, a table presenting all parameter values would be helpful.**

A table with all used parameters is now presented (Table 3).

---

P7515 L5ff: **Glacier evolution: some words about the methodology and its use are required before diving into the results.**

The methodology of the glacier evolution model is now described in Section 4.1. We think that is sufficient and does not have to be repeated here. See response to first comment about "paper structure/method" of reviewer 1 (Bettina Schäfli).

---

P7515 L13 **'..in total ice mass' (not 'masses')**

"Only a short period of mass gain was observed between 1978 and 1983, when the ice volume increased by about 192 mio m corresponding to an increase of 3.6 % in total ice *mass*."

---

P7515 L14 **'Independent of the size.. ' (erase 'ly')**

"*Independent* of the size, all glaciers in the Mauvoisin region will severely retreat in the future."

---

P7517 L1 **'..decrease...BY..' (not 'of')**

"This shift of the peak discharge from end of July to the mid of June results from the decrease of the runoff volumes in the months July to September *by* about 44% compared to the reference period."

---

P7517 L24 **'In contrast..', there is no contrast. Link the sentences for instance using 'Further..'**

"*Further*, solid precipitation will suffer a decrease of about 33 % over the same period."

---

P7517 L26 **'..The runoff FROM..' (not 'of')**

"The runoff *from* non-glacierized areas and the subsurface will not change significantly in the future".

P7518 L2	<p><b>‘. . .the ice thickness to be DETERMINED. . .’ (not ‘delineated’)</b></p> <p>“Extensive helicopter-borne GPR measurements allowed the ice thickness distribution in the Mauvoisin area to be <i>determined</i> accurately.”</p>
P7518 L2	<p><b>. . .’quite accurately’. Do you have a sense of the accuracy? Can you quantify it? (for instance by comparison to ground GPR).</b></p> <p>We reformulated the sentence:</p> <p>“Extensive helicopter-borne GPR measurements allowed the ice thickness distribution in the Mauvoisin area to be determined <i>accurately</i>.”</p> <p>The section about the uncertainties of the GPR data contains now information of the comparison between the ground-based and the helicopter-based GPR measurements to show how accurate GPR measurements are.</p>
P7518 L7	<p><b>‘. . .five different ice thickness DISTRIBUTIONS’ (not ‘distribution estimation procedures’ which is awk)</b></p> <p><b>Add a reference to Fig8.</b></p> <p>“For that purpose, we considered five different ice-thickness <i>distributions</i> (Fig. 8):”</p>
P7518 L17	<p><b>MACRO-scale (not ‘marco’).</b></p> <p>“This distribution is the most simple case and is used in most <i>macro</i>-scale hydrological models where ice volume is crudely processed (Fig. 8d).”</p>
P7519 L9	<p><b>‘The different ice volume distributions significantly affect. . .’</b></p> <p>“The different <i>ice volume distributions</i> significantly affect the runoff projections.”</p>
P7519 L13	<p><b>Reference should be to Fig10 instead of Fig6.</b></p> <p>Ok! Due to the two new figures it is now Figure 12 instead of 10.</p> <p>“Afterwards, the runoff volume starts to decrease gradually until 2100 (Fig. 12).”</p>
P7519 L20	<p><b>Remove ‘specific’.</b></p> <p>“<i>Neglecting a spatial ice volume distribution</i> by assuming uniform ice thickness distribution (4) leads to an overestimation of the runoff in the next two decades due to too large ice masses at low altitude.”</p>
P7519 L22	<p><b>‘. . .AT low altitude’ (not ‘in’).</b></p> <p>“<i>Neglecting a spatial ice volume distribution</i> by assuming uniform ice thickness distribution (4) leads to an overestimation of the runoff in the next two decades due to too large ice masses <i>at</i> low altitude.”</p>
P7520 L4/5	<p><b>‘. . .emphasizes the importance of. . .’ importance for what?</b></p>

“The ice volume sensitivity study emphasizes the importance of an accurate ice volume determination *for glacier and runoff projections.*”

---

P7520 L7 **‘Inaccurate estimations. . .WILL CAUSE. . .’**

“Inaccurate estimations of the total ice volume *will cause* deviations from the predicted general runoff trend.”

---

P7520 L19ff **‘. . .sensitivity of the correction factor on the ice volume.’ the opposite is true: the ice volume estimation is sensitive to the correction factor!**

“*Due to the high sensitivity of the ice volume estimation on the correction factor* (Farinotti et al, 2009b) the usage of an appropriate correction factor is of much higher importance compared to the mass balance gradients.”

---

P7520 L23 **L23: ACCURACY (misspelled: accruacy).**

“Knowledge about the local ice-thickness enables the calibration of the correction factor resulting in a significantly increased *accuracy* of the ice volume estimation.”

---

P7521 L4 **‘geometry of the bed topography’ is a pleonasm. Use either ‘geometry of the bed’ or ‘bed topography’**

“Despite the high density of ice-thickness measurements and the application of an ice-thickness estimation method, the true *bed topography* is not fully known.”

---

P7521 L29ff **‘melt parameters are sensitive for runoff projections’, the opposite is true: runoff projections are sensitive to changes in the runoff parameter values.**

“*The study of Farinotti et al. (2012) reveals that runoff projections are particularly sensitive to changes in the temperature gradient and melt parameters values.*”

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P7522 L4 **‘temperature distribution has a big impact. . .’ one more reason to better explain how the temperature was distributed! (more details about lapse rates etc. . .).**

See answer to comment P7514 L7.

---

P7522 L28 **‘. . .further increases the complexity of the accumulation pattern’**

“Variable redistribution of snow by wind and avalanches *further* increases the complexity of the accumulation pattern (Lehning et al, 2008).”

---

P7522 L29ff **This is a model description and should be placed in the corresponding section.**

This sentences was placed in section 4.1 “Glacio-hydrological model.

---

P7523 L7 **‘. . .by which . . . were determined’**

“This served as input for a combined glacio-hydrological model (Huss et al, 2008; Farinotti et al, 2012), *by which* glacier and runoff projections *were determined.*”

---

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P7523 L10ff: **Present the result of volume estimation after the first sentence of this paragraph.**

*“In this study we combined results from extensive GPR measurements with an ice thickness estimation approach (Farinotti et al, 2009), for determining the present ice volume in the Mauvoisin area. A total ice volume of  $3.69 \pm 0.31$  km was calculated by including all available measurements and a maximal ice-thickness of 291 m was found. The derived ice volume distribution served as input for a combined glacio-hydrological model (Huss et al, 2008; Farinotti et al, 2012), with which glacier and runoff projections could be determined. By means of a sensitivity analysis we could demonstrate that an under- or overestimation of the total ice volume may lead to severe distortions or the runoff projections and potentially even to deviations from the projected general runoff trend.”*

---

P7523 L13 **This is not a prophecy but a model result. put into perspective by adding an 'According to our model. . .'**

*“According to our model the annual runoff will slightly rise in the next few decades to a maximum of 275 mio m<sup>3</sup> a<sup>-1</sup> around 2030.”*

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P7523 L20 **'Reasons . . . ARE. . .'**

*“Reasons for these changes are the strong decline of the glacier melt supply, the decreasing snow melt contribution and the earlier initiation of the snow melt season.”*

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Reference list **The citation formats for the following entries is quite unusual and should be rectified: BFE, CH2011, IPCC, RST, VAW.**

We followed the reference suggestion of the IPCC and CH2011 report where they suggest citing the reports as “(IPCC, 2007)” and “(CH2011, 2011)”. The reference to “(VAW, 1998a)” is also kept, because it is an institutional report with no specific author.

The other references were adapted according to the suggestion:

- (*Bundesamt für Energie, 2011a*) instead of (BFE, 2011a);
  - (*Bundesamt für Energie, 2011b*) instead of (BFE, 2011b);
  - (*Radar Systemtechnik GmbH, 2012*) instead of (RST, 2012);
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Tables

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Tab. 4 **The uncertainty presented with the values for V(1), what does it represent? (standard deviation, mean error. . .?) where does it come from?**

According to the new analysis about the uncertainties of the GPR measurements and ice volume estimation, the ice volumes V(1) in Table 4 were updated. The uncertainties showed in Table 4 represent standard deviations and are computed on the basis of the uncertainties introduced by the GPR measurements and the interpolation method. The caption of Table 4 was improved in order to provide more clarity.

Caption Table 4:

*“Area, maximal (H<sub>max</sub>) and mean (H<sub>avg</sub>) ice thickness, ice volume of (1) (V(1)) with standard deviation, ice volume of (5) (V(5)), the relative ice volume difference between V(1) and V(5) (V(5:1)), and the calibrated apparent mass balance gradients for the ablation (db/dz<sub>abl</sub>) and accumulation zone (db/dz<sub>acc</sub>) of the Mauvoisin region.”*

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**Also the presented value for the correction factor c: is that a mean value for the glacier? Can you provide an uncertainty value for c?**

Unfortunately, the column with the calibrated c-factors is a remaining of an older version of the paper in which a sixth ice volume distribution was considered in the ice volume sensitivity analysis. This additional case operated with an ice volume distribution which was derived by ITEM, but with calibrated c-factors (by the GPR measurements). The resulting annual runoff evolution of this case is very similar to case (1) and was neglected in order to avoid confusion.

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Figures

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Fig. 1 **‘. . .The inset on the bottom RIGHT. . .’ (not ‘left’) ‘. . .shows the location of the catchment WITHIN SWITZERLAND’**

“The inset on the bottom right shows the location of the catchment *within* Switzerland and the weather stations used in this study.”

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Fig. 2 **Why are the elevation values on the y-axis negative?**

The negative y-axis values of Figure 2 were corrected.

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Fig. 4 **What does the shaded area represent? The median (line) and the 5% and 95% percentiles of the ensemble of model results?**

We added further information about the hatched area in the caption of Fig. 4.

“Ice volume evolution in the Mauvoisin region between 1900 and 2100. *The hatched zone represents the 95% confidence interval for the past given by the computed ice volume uncertainty and for the future given by the 100 different model runs.* Black triangles and corresponding dotted lines show years in which a DEM is available.”

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Fig. 7 **‘. . .AVERAGED over. . .’**

“Evolution of the runoff regime in the Mauvoisin region for the reference period and four time snapshots in the future *averaged* over  $\pm 5$  years (top).”

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Fig. 7 **Fig7 label the individual figures with a-e.**

Ok!

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Fig. 9 **‘. . .derived FROM the GPR measurements. . .’**

“The thin black line refers to the glacier bed derived *from* the GPR measurements, the thin gray line to the bed computed by the ITEM and the blue line to the glacier surface.”

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Fig. 10 **Refer to Section 5 instead of Chapter 5.**

“The numbers in brackets refer to the different initial ice volume distributions presented in

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Fig. 10

**The runoff projection for V5 starts at a lower level than the others, suggesting a smaller glacierized area. Later on the runoff related to V5 is the highest and reaches its peak last, indicative of a larger ice volume than the other estimations. Smaller area but larger volume -> overestimated ice thickness? Any comments on this?**

The initial glacierized area is in all ice thickness distributions the same. Thus, the glacierized area has no influence on the difference between the different ice volume distributions. The timing of the maximum annual runoff depends on total initial ice volume and on its distribution. At the start of the projection all runoff evolutions should start at the same level. By generating the figure, the past runoff evolution was neglected in the smoothing process and therefore the different projections start at different levels. An improved figure was added.

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