Response to report # 2

The authors of the manuscript thank the referee for his positive evaluation of the manuscript and for his comments, which helped improving the manuscript.

Detailed responses to all components are given below (blue).

This manuscript proposes to quantify the origin of streamflow in a Himalayan basin, using a physically-based snow hydrological model.

The underlying research question is interesting for the readership of HESS but I have the following major concern:

In this paper, two definitions of the origin of streamflow are used: A) annual contributions of snow fall, rainfall and ice melt to total runoff, and B) fractions of contributions coming from different areas. Both definitions can answer different questions and both are certainly useful. But my main question is: Is the water partitioning and associated water flowpaths reliably enough represented in the used hydrological model to give reliable answers under definition A and B? What evidence do you have for such a reliable representation?
Based on the model description, I am not confident that this is the case.

Overall, the paper does not yet convincingly convey that the obtained results reliably represent the dominant hydrological processes. The paper validates snow and glacier mass balance simulations but no evidence is provided for a reliably parameterization of water partitioning and release from the subsoil.
The validation of the model output was established on discharges at different time scales, the snow cover area, and glacier mass balances in order to validate the simulations of the snow cover, glacier melt and discharges separately. The results demonstrate that the new version of the model performs well for all three signals. Therefore, we are confident that the new implementation improved the quality of the represented processes and increases the reliability of the quantification of the ice melt, snow melt and rainfall contributions (definition 1).

There is no existing data to validate subsurface and groundwater flows making it difficult to assess the reliability of the contributions estimated with definition 2. Although these results are subject to a significant uncertainty, we think that addressing the question of the definition of the contributions and comparing the results obtained with two definitions is interesting for the glacio-hydrological community.

In order to present our approach more clearly, the “Results and discussion” section of the manuscript will be rearranged to:

- in a first part, present the contributions to the outflow simulated in the Pheriche catchment with an improved version of the glacio-hydrological model,
- in a second part, discuss all the limitations to the quantification of the contributions to the outflow (representation of the processes in the model, parametrization, initialization and water partitioning). In particular, a discussion concerning the uncertainty related to the partitioning between direct and delayed contributions will be added.

Delayed water release by glaciers is e.g. emulated with a deep soil under glaciers (as far as I understand), which does not necessarily give wrong results but the implications should be clearly discussed.
A test of sensitivity of the soil water depth under glaciers on the simulated hydrological response will be added in the manuscript. The results are presented in the supplementary information (below).

Detailed comments:

- Abstract: it is stated that “In general, it is shown that the choice of a given parametrization for the snow and glacier processes has a significant impact on the simulated water balance.” Should there not be a more quantitative statement, including why the approach is nevertheless deemed useful to quantify the origin of water?

Replaced by: “The choice of a given parametrization for the snow and glacier processes has a significant impact on the simulated water balance: the different parametrizations tested in this study lead to an ice melt contribution to the outflow ranging from 45 to 70 %.”

I suggest mentioning all used validation data in the abstract (MODIS, mass balances)
Sentence added in the abstract: “The validation of the snow, glacier and hydrological processes was established using three types of validation data (MODIS images, glacier mass balances and in situ discharge measurements).”

- Introduction: it would be nice to better say why it is interesting to know the proportion of snow / ice melt and rainfall. One reason is that this can give insights into how much water is seasonally delayed and that this delay might change in the future. Another reason is that snow melt / ice melt might have a completely different hydrological pathway (in particular in terms of groundwater recharge) than rainfall. This might e.g. cause a shift in the overall water balance if the ratio snowfall to rainfall changes (Berghuij Woods, Nature Climate Change, 2015). Another interesting question is how much water is currently available that has been accumulated long time ago in the glaciers.
The motivations for quantifying the contributions to the outflow should indeed be more explicit in the introduction. Thank you for these improvements which will be added in the introduction.

- How does the model handle transpiration by vegetation? The loss via transpiration should be accounted for in the equations 4- 7 to quantify runoff production
In DHSVM-GDM, the losses by evapotranspiration are withdrawn from the soil moisture. As there is no possibility of knowing the partitioning between ice melt, snow melt and rainfall in the soils simulated by the model, the contributions estimated with the definition 1 are calculated based on the volume of liquid water reaching the soil surface, i.e. before evapotranspiration.

Thank you for this remark, there is indeed an error in the equations 4 – 7 which was corrected as following:

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Vrunoff = Vicemelt + Vsnowmelt + VrainNet
Vicemelt = VglAcc - Sice – dIwq/dt
Vsnowmelt = Psolid - Ssnow - VglAcc – dSwq/dt
VrainNet = Pliquid - Eint
Q = Vrunoff + ET
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“Where VglAcc is the amount of snow that is transferred to the ice layer by compaction on glaciers (Naz et al., 2014), Sice and Ssnow are the amounts of sublimation from the ice and snow layers, dIwq/dt and dSwq/dt are the variations of the ice and snow storages, Psolid and Pliquid are the amounts of solid and liquid precipitations, and Eint is the amount of evaporation from intercepted water stored in the canopy.
It is worth noting that the sum of these contributions Vrunoff is not equal to the outflow at the catchment outlet Q as it represents all liquid water reaching the soil surface (before infiltration in the soils and glaciers and before evapotranspiration ET).
Moreover, at daily or monthly time scale, Vrunoff may not be equal to Q - ET as liquid water can be stored by or evacuated from the soil or glaciers.”

- Results on winter flows controlled by release from the englacial water storage: what are the similar results in the literature? What provides confidence that the model parameterization is reliable?
Several studies have shown the role of the storage changes on the winter outflow in this region.
In the Langtang region, Ragettli et al. (2015) found that “storage changes (derived from changes in soil-, channel-, surface- and englacial reservoir volumes) are the most important contributors to runoff during winter”.
Similar results were found by Racoviteanu et al. (2013): “Mixing models showed groundwater to be an important component of river flow within only tens of kilometers of the glacier outlets in the post-monsoon season”.

With this model parametrization, it is difficult to separate groundwater and englacial flows, that’s why the sentences p.21 l.10-13 will be replaced with:
“Figure 13b shows that groundwater and englacial water contributes to more than 50 % of the outflow during the monsoon season and can contribute up to 90 % during winter. This corresponds well to the studies of Ragettli et al. (2015) and Racoviteanu et al. (2013) concerning the Upper Langtang and the

Dudh Koshi basin respectively, who found that most of the winter outflow surges from soil and englacial storage changes."
As stated above, a discussion about the uncertainty on the estimation of the delayed contributions with DHSVM-GDM will be added in the revised manuscript.

- Throughout the paper: what is net rainfall? There is no generally accepted definition.
In this study, net rainfall is defined as the liquid precipitation minus the interception by the vegetation (equation 7).

- The cited observed geodetic mass balances have a very wide range of uncertainty and stem from different areas / different time periods. It is unclear why they are nevertheless useful for validating the modelling results. This should be justified. If the geodetic estimates are from a completely different period (period is not given), this might be questionable.
The in-situ punctual mass balances and the geodetic mass balances are used as complementary data for the glacier mass balances validation.
The geodetic mass balances are indeed estimated on different periods but these data give an order of magnitude of the glacier mass balances at the basin scale whereas the punctual mass balances only allow to validate the ice melt on the White Changri Nup and Pokalde glaciers, which are not representative of all glaciers in the basin.
Moreover, the White Changri Nup and Pokalde glaciers are two debris free glaciers and the punctual mass balances do not allow to validate the reduction factor on debris covered glaciers added in the model: on Figure 9, the comparison between the simulated glacier mass balances at the basin scale and the geodetic mass balances clearly shows that the configurations v1 and v2 lead to unrealistic glacier mass balances and that the debris layer on glaciers needs to be taken into account in order to simulate correct mass balances in the catchment.
For this type of highly glacierized catchments, using validation data from both local and global scales seems to be the best way to analyze the performance of the model for glacier melt simulation.

- Figure 10: I do not clearly see which model version is the best; in terms of RMSE, v3 might (slightly) outperform v0. What about the bias? Is it a good or a bad thing that v0 has less variability of the point mass balances than v3?
For the Pokalde glacier, the v0 and v3 RMSE values are similar but the configuration v3 leads to a bias ten times smaller than v0 (mean bias of 1 m with v0 and 0.1 m with v3).
V3 shows a larger variability but the point mass balances are spread around the diagonal axis. This is not the case with the configuration v0 which clearly always overestimates the mass balances.

- Gauging curve uncertainty: what is the design of the gauge? Does the cross-section move? Is the uncertainty estimate not far too conservative? Please provide more details than "A 15
The gauging station is located in gorges downstream from the village of Pheriche. The geometry of the measurement section was stationary. We did not observe any change of the channel cross section.
The river stage was measured every 30 minutes with a pressure transducer (resolution -/+ 1 mm). 44 discharge measurements were performed using a tracer (fluorescein) dilution method (sudden injection). The tracer concentrations were measured each 5 seconds in the river downstream of the mixing zone using a fluorometer. A calibration was completed in the field for each gauging. This method is a powerful tool for measuring stream discharge, especially in steep, rough streams that cannot be gauged accurately using the velocity-area method (Hamilton and Moore, 2012). These measurements cover a range of water stages representing 95% of the range of variation observed during the study period.
The global uncertainty associated with a discharge time serie combines three main sources of errors: the uncertainties in the discharge measurement, in the measurement of stage, and in the plot of the stage-discharge relationship (Tomkins, 2012). In the case of natural channels it is difficult to predict this uncertainty precisely. In this study an estimation of its magnitude was proposed at 15%. This estimation combines the 3 sources of uncertainty: discharge measurements by dilution method (5 %); the uncertainties in stage measurement and time interpolation were considered as negligible and the uncertainty of the rating curve (10 %). These estimations were found in the literature (Di Baldassarre and Montanari, 2009; McMillan et al., 2012).

Di Baldassarre, G., Montanari, A., 2009. Uncertainty in river discharge observations: a quantitative analysis. Hydrol. Earth Syst. Sci., 13, 913–921. doi:10.5194/hess-13-913-2009

Hamilton, A.S., Moore, R.D., 2012. Quantifying Uncertainty in Streamflow Records. Canadian Water Resources Journal 37, 3–21. doi.org/10.4296/cwrj3701865

McMillan, H., Krueger, T., Freer, J., 2012. Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. Hydrological Processes 26, 4078–4111. doi.org/10.1002/hyp.9384

Tomkins, K.M., 2014. Uncertainty in streamflow rating curves: methods, controls and consequences. Hydrological Processes 28, 464–481. doi.org/10.1002/hyp.9567

- General comment on conclusion: I strongly suggest to separate the discussion from the conclusion, it is very unusual to discuss results in the conclusion section

The structure of the revised manuscript will be modified to separate the discussion and conclusions sections.

- Conclusion: can you really affirm that the model has an improved parameterization of the storage and transport of melt water within glaciers, or is the modified model just emulating it with the selected parameters?

There is indeed no representation of the storage and transport of melt water within glaciers in the modified version of the model as we used the soil parameterization to compensate this. We replace the following sentence:
“In this study, an improvement of the parameterization of cryospheric processes in DHSVM-GDM was proposed in order to better represent ice melt under debris covered glaciers, avalanches, the storage and transport of melt water within glaciers.” (p.25 l.11-13)
with:
“In this study, an improvement of the parameterization of cryospheric processes in DHSVM-GDM was proposed in order to better represent ice melt under debris covered glaciers and avalanches”

- Conclusion: instead of just stating that “The albedo parametrization (..) enabled to simulate the snow cover spatial distribution and the glacier mass balances more accurately”, would be useful to refer to the validation data used

Replaced with:
“Simulated SCA were compared with MODIS images and calculated glacier mass balances with local in situ measurements and geodetic mass balances. The parametrization proposed in this study and the implemented avalanche module enabled to simulate the snow cover spatial distribution and the glacier mass balances more accurately than in the original version of DHSVM-GDM by increasing the glacier accumulation and reducing ice melt.” (p.25 l.14-16)

- Conclusion: “water is withdrawn every year from the catchment through ice melt”; strange formulation, difficult to understand; better something like “part of the streamflow leaving the catchment results from negative glacier mass balance changes”.

- Conclusion: “Thus, if the precipitation regime (in terms of both intensity and phase) does not change within the next decades, the access to water resources is likely to be reduced, especially during the fall and the winter seasons, as the glaciers outflow will decrease due to glaciers shrinkage, even without taking into account climate warming.” This sentence should be deleted, it is pure guessing and perhaps wrong. Continued glacier retreat means continued negative mass balances, means water input in addition to annual precipitation. The moment of peak water remains to be determined.

We agree to delete this sentence.

- I am not a specialist in debris covered glaciers but I think that there should be some more literature review on how important a good representation of debris cover in glacio- hydrological models is, especially in the Himalaya

Debris covered glaciers represent about 23 % of all glaciers in the Himalaya-Karakoram region (Scheler et al, 2011). The debris layers have been expanding during the last decades due to the glacier recession (Shukla et al, 2009, Bhambri et al, 2011, Benn et al, 2012) and are expected to keep expanding in the near future due to global warming (Rowan et al, 2015).

The debris thickness has a strong impact on the meltwater generation (Vincent et al, 2016 found a reduction factor of 0.4 between the ablation on debris covered areas and debris free areas on the

Changri Nup glacier) which means that a good representation of the debris covered glaciers in glacio-hydrological models is essential for estimating the right amount of meltwater generated in glacierized catchment in the Himalayas.

Quantification of different flow components in a high-altitude glacierized catchment (Dudh Koshi, Nepalese Himalaya). Supplementary information

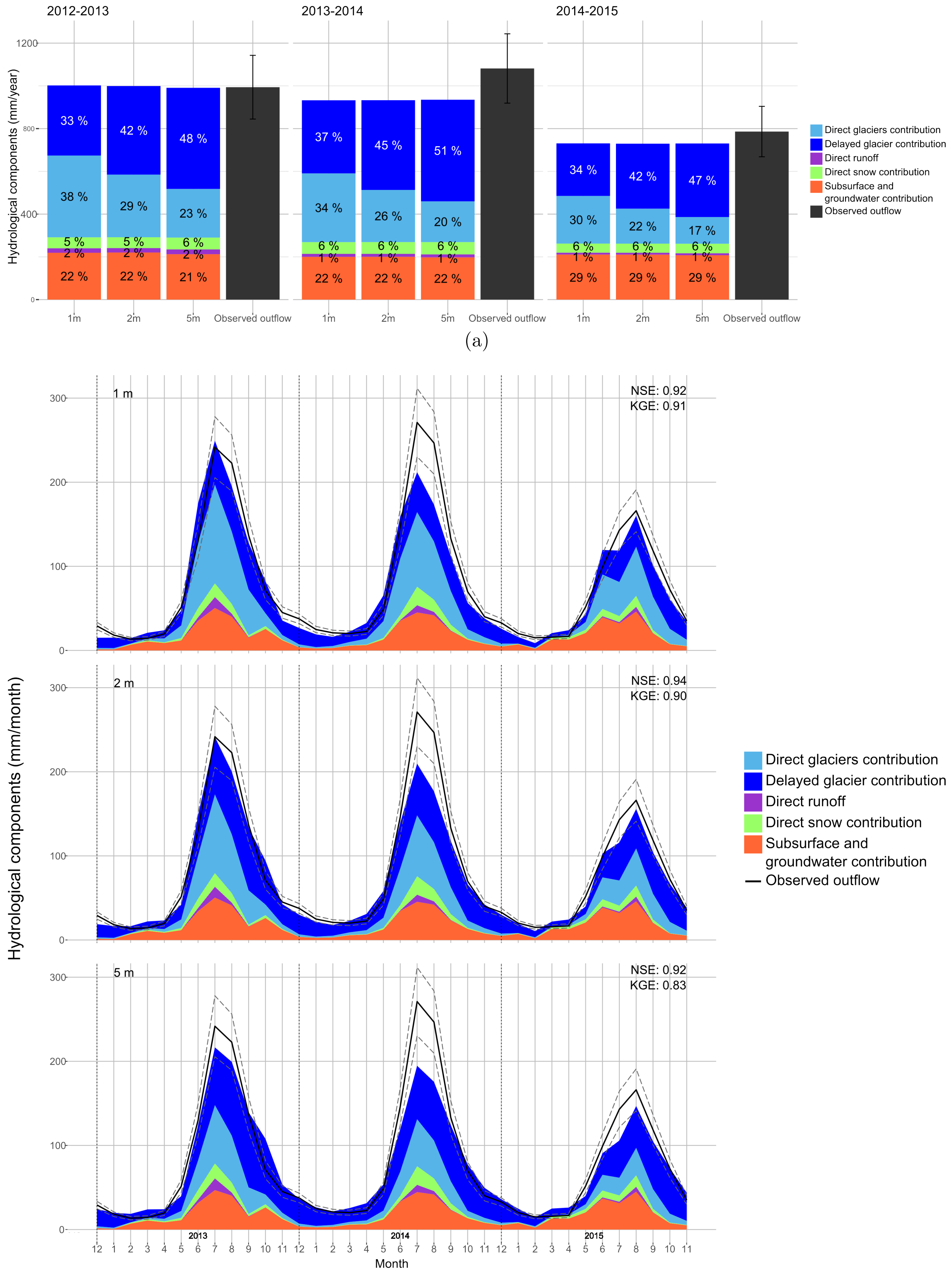
May 16, 2018

1 Sensitivity of the soil depth under glaciers on the simulated discharges

Three different values of soil depth under glaciers were tested in order to assess the sensitivity of the soil depth under glaciers on the simulated discharges. Figure 1 shows the simulated discharges and flow components simulated with configuration v3 for a soil depth under glaciers equals to 1 m, 2 m and 5 m.

Figure 1a shows that the soil depth under glaciers does not impact the simulated annual outflow and the total annual contributions from glacierized and non-glacierized areas. The soil depth under glaciers only impacts the partitioning between direct and delayed contributions (soil water and englacial water contributions): when the soil depth under glaciers ranges between 1 m and 5 m, the direct glaciers contribution ranges from 34 to 20 %, and the delayed glacier contribution ranges from 35 to 47 %.

An increasing of the soil depth under glaciers leads to a delay of the outflow as there is more infiltration simulated during the pre-monsoon and monsoon seasons, but this has a limited impact on the NSE and KGE values (see Figure 1b).



(a)

(b)

Figure 1: a) Annual and (b) monthly discharges and flow components (definition 2) simulated with configuration v3 with three different soil depths under glaciers (1 m, 2 m et 5 m). Observed monthly discharges are represented with an interval of uncertainty of 15 % (dashed back lines).