Author responses to comments Reviewer #1 (Review of hess-2021-512)

This paper proposes to quantify the contribution of ice melt to total streamflow in three highly glaciated catchments in the central Swiss Alps with the help of stable isotopes of water. The aim is to come up with results that are more reliable than previous modelling-based results and with recommendations for future sampling campaigns.

1. I cannot recommend the paper for publication because some fundamental hydrological process knowledge is ignored. The obtained results are not plausible (glacier melt contribution of between 80% and 95% to total streamflow during August in catchments with only between 6 and 28% glacier cover). One key result is summarized in Figure 8, which shows glacier melt in Mio m3 against glacier area. For the smallest glacier investigated, this result indicates meltwater production of 4*106 m3 on an area of 0.3 km2, which corresponds to a melt water production of 4*106 m3/0.3*106 m2 = 13.3 m of melt water production over the glacier area. For the largest glacier, it is 18*106 m3/6.8*106 m2 = 2.7 m of meltwater production. The first value is impossible, the last value is in the order of observed summer mass balances in Switzerland in 2019 (see Figure 1 one in the attached complete review).

We thank the reviewer for this highly important estimation and we acknowledge that we should have done this plausibility calculation by ourselves. However, in our opinion, these estimations also illustrate that our quantification of the glacial meltwater contribution worked for the catchment with the highest degree of glaciation (Steinwasser). Moreover, the high variability of the electrical conductivity (EC) data in the Steinwasser catchment compared to the other two catchments (Fig. 6 of the original manuscript) demonstrates that the relative groundwater contribution to the mountainous streams the is much lower compared to the other two catchments. Consequently, the glacial meltwater production estimated by Reviewer #1 for the Steinwasser catchments yielded reasonable results because the groundwater contribution is low compared to the other catchments. This sets an important limitation for using stable water isotope data to quantify glacial meltwater contributions to mountainous streams such that the stable isotope method works if the groundwater contribution is low. We plan to highlight this in the revised version of the manuscript if we are allowed to revise the manuscript.

2. The reasons for the erroneous estimates are certainly related to the wrong assumption that streamflow during summer is only composed of glacier melt and of rainfall. In reality, an important part of streamflow is groundwater (baseflow) released by the hillslopes; the isotopic values of groundwater are strongly influenced by snow melt and thus close to the values of glacier melt (see below). Accordingly, the separation into glacier melt and not-glacier melt is impossible with the help of isotopes alone. EC values could help separating ground water from non-groundwater input but this would require values for groundwater and values for ice melt at the glacier snout (which was already in contact with the ground).

As discussed in the general response to the reviewer's comments, we agree that our partially erroneous estimates of the glacial meltwater contribution to mountainous streams are related to the negligence of the groundwater as an interim storage for all end-members (snowmelt, glacial melt, rainwater). Also, we agree that EC values are crucial for identifying a significant groundwater contribution to the streamwater samples. For instance, the high EC variation observed for the Steinwasser catchment (Fig. 6) is likely inherited from a lower groundwater contribution compared to the Wendenwasser and Gigli catchments showing much lower EC variations typical of groundwater-dominated streams. However, groundwater is not an independent end-member because it consists of a mixture of the three endmembers (snowmelt, glacial melt, rainwater). Thus, in our opinion, quantifying the groundwater component does not significantly help to get better estimates for the contribution of the rainwater, snowmelt, and glacial melt contribution in a specific streamwater sample. This is also because the EC value of the groundwater component is mainly controlled by the overall degree of mineral dissolution reactions occurring in the subsurface and thus, the subsurface residence time of the groundwater body, and not by the contribution of the three end-members in a specific groundwater sample.

3. The analysis of the contribution of ice to streamflow is based on a total of 2 ice melt samples taken each from a different glacier, both located in only one of the three catchments, i.e. there are no ice samples in two of the catchments. One catchment has no snow samples, all snow samples have (according to the sampling location figure) been taken at low elevations, there is only a total of 19 snow samples (the paper does not contain a clear overview of dates and elevations when and where the snow samples were taken). Ice melt can have considerable variability (Figure 2) and be overlapping with the values of snowmelt and of the snowpack (Figure 3). Since groundwater is strongly influenced by snowmelt, it most likely has isotopic ratios that are also rather low.

In our opinion, the low number of glacial meltwater samples does not majorly affect the main conclusion of the paper since it has been previously shown that the isotopic variability of glacial melt water is low compared to snow and rain (Müller et al., 2021; Schmieder et al., 2018; Zuecco et al., 2019). In addition, the data that reviewer 1 shows in figure 2 displays a δ^2H variation of 6‰ (-106 - -112‰) for glacial meltwater. A similar δ^2H variation of was observed in our samples (-93.6 - -95.3‰). Moreover, the variation in δ^2H in figure 2 shown by the reviewer corresponds to a variation of around 0.75‰ in δ^{18}O being also in the range of our samples (-12.83‰ vs. -13.33‰). Hence, we think that we captured the isotopic variability of the glacial meltwater with our samples and that they are representative for the glacial meltwater in the mountainous streams.

Regarding the 23 snow samples, it is correct that they originate from only one catchment. However, given that the outlets of the three catchments are located within a distance of only about 2 km (Fig. 1 of the original manuscript), we do not think that this is an issue. The sampling dates and exact coordinates are all provided in the data repository (see line 557 of the original manuscript). However, we agree that we should provide at least the sampling altitudes in a table of the main manuscript. This will demonstrate that the snow samples were collected at different altitudes ranging from 1541 to 2169 masl. We would also like to emphasize that we have collected the snow samples during a period of 13 months (February 2019-March 2020), which included the winter months where the catchments were only accessible by helicopters. We are confident that the resulting snow stable isotope data presented in Fig. 4 represent a unique dataset for obtaining new insights into the processes causing the temporal variation of the stable isotope signature of alpine snow packs. For the revised manuscript, we plan to provide a more in-depth interpretation and discussion of this highly interesting and unique dataset if we are allowed to revise the manuscript.

We also agree that groundwater is influenced by snowmelt but we are not convinced that snowmelt is the only source. Instead, groundwater likely represents a mixture between snowmelt, rainwater and glacial melt. Owing to the elevated residence time we expect that groundwater δ^2H and δ^{18}O values reflect an average signature defined by the mean annual contribution of snowmelt, glacial melt and rainfall as the three main water sources.

4. Figure 2: delta-Deuterium values in ice melt samples from the Otemma glacier (Müller et al., 2021), see also the display material here: https://presentations.copernicus.org/EGU21/EGU21- 7182_presentation.pdf

Unfortunately, the indicated link does not work so we could not find the indicated material.

5. Introduction: There is no reference to mixing analysis in the introduction despite of the huge body of hydrologic literature in this field. There is very little reference to isotopes studies in Alpine areas (e.g. Penna et al., 2014)

We acknowledge that we have to extend the introduction regarding this topic. This will be done in the revised version of the manuscript if we are allowed to revise the manuscript.

6. The text mentions the enrichment in heavy isotopes in the snowpack over the accumulation season and attributes it to melt/refreeze cycles and moisture exchange with the ground. This explanation is a priori not plausible for enrichment during the accumulation phase at elevations around 2000 masl (exact sampling elevations unknown) where ground is often frozen in winter and melt only occasion. However, the sampled period might well correspond to an exceptionally warm winter. This should be specified. We would need actual temperature recordings to shed light on this.

We agree that moisture exchange with the subsurface is not possible and that moisture exchange with the atmosphere is more likely to have caused the observed stable isotope shift. In the revised manuscript, we will provide an extended interpretation and discussion of the data shown in Fig. 6 if we are allowed to revise the manuscript.

The exact sampling locations are provided in the data repository and we will list the sampling altitudes in the main part of the revised version of the manuscript if we are allowed to revise the manuscript.

7. Line 283: mistake, “The more enriched d18O and d2H snow values in the ablation compared to the ablation period”.

Correct, the second time “ablation” should be replaced by “accumulation”. We will correct this issue in the revised manuscript if we are allowed to revise the manuscript.

8. Line 288: I would not interpret a single solid ice sample with respect to two ice melt samples.

Well, the samples were taken at the same time and we think it is an interesting observation because it demonstrates that during ice melt, stable isotope ratios can change. We agree, that the interpretation is challenging though.

9. Line 363 following: would be more interesting to compare the streamflow in terms of specific discharge (normalized to catchment area), in mm/d, (and thus remove the log-scale in the figure)

We agree with the reviewer and we will apply the suggested change when preparing the revised version of the manuscript if we are allowed to revise the manuscript.

10. Line 381: “The significant contribution of snow and glacial meltwater to the stream discharges is further reinforced by the low electrical conductivity (E.C.) in the Steinwasser

catchment discharge (~ 30 µs/cm) between June and August 2019 (Fig. 6C)": you omit that the two others seem to have values of around 100. Do you have any groundwater / spring sample to judge how high this is?

In fact, we did collect spring samples (i.e. groundwater) close to the outlet of the Wenden- and Steinwasser catchments. For the Wendenwasser spring, we measured 148 and 149 µS/cm on August 23 and September 16, 2019, respectively. For the Steinwasser spring, we measured 63 µS/cm on October 3 2019. These measurements are fully consistent with the statement the reviewer referred to (line 381) and we plan to add them to the manuscript and to provide a corresponding discussion when preparing the revised version of the manuscript if we are allowed to revise the manuscript.

11. Line 389 following: you make the point that during winter low flow, which is dominated by groundwater, the separation of streamflow components (rain, snow, ice) is difficult. This applies also during the rest of the year

We agree with the reviewer. As described in the general response to the reviewer's comments, we plan to change slightly the scope of the manuscript to focus more on the opportunities, challenges, and limitations of using stable water isotopes for the quantification of glacial meltwater contributions to mountainous streams.

12. Line 405 following: do you have evidence of the absence of snow in August and September? Perhaps at least the largest glacier has still a firn / permanent snow area? Even for the other two glaciers, snow might persists in August and might come back in late September? Complete absence might hold maximum for a week or two. Snow might even persist in August in shady areas outside the glaciers?

The reviewer is right, we cannot completely exclude the presence of firn and the absence of patchy snow in shady areas. However, the observation that our quantification approach results in reasonable glacial meltwater contributions to the stream in the Steinwasser catchment, characterized by a low groundwater contribution (see general response to the reviewer's comments above), suggest that the error introduced by this simplification is rather small.

13. Line 415: you could test the sensitivity of the results to a lapse rate in precipitation, since you have such an effect for part of the year as far as I understood?

The reviewer is right, this could and will be tested when preparing the revised manuscript if we are allowed to revise the manuscript.

14. Line 420: "it can be expected that the isotopic signature of the melting ice changes minimally between in August and September (Beria et al., 2018)." Different locations on the glacier might show different values for melt; but the actual problem is that the hillslopes provide high baseflow, which has isotopic values of groundwater, which in turn has the values of snow;

We agree, as described in the general response to the reviewer's comments, the quantification of the glacial meltwater contribution to mountainous streams is highly challenging if a strong groundwater contribution occurs. However, we would like to emphasize that the stable isotope values of groundwater samples depend on the contribution of snowmelt, glacial melt and rainfall in the groundwater. Owing to the elevated residence time we expect that groundwater δ^2H and $\delta^{18}O$ values reflect an average signature defined by the mean annual contribution of snowmelt, glacial melt and rainfall as the three main water sources.

15. Line 424: your main result with very high glacier melt shares for all three catchments is not in-line with your EC measurements?

We agree with the reviewer. As mentioned in the general response to the reviewer's comments, we acknowledge that only the glacial meltwater contribution to the streams for the Steinwasser catchment is plausible.

16. Figure 8: fitting a power-law to three points is clearly over-fitting?

As described in in the general response to the reviewer's comments, we plan to slightly shift the scope of the manuscript and we will no longer provide fully quantitative estimates of glacial meltwater contribution for the Giglibach and the Wendenwasser catchment. Therefore, Figure 8 will be removed when preparing the revised version of the manuscript if we are allowed to revise the manuscript.

References

Müller T., Schaefli B. and Lane S. N. (2021) Assessing the effect of the geomorphological complexity of glacier forefields on the multi‐temporal water dynamics will provide better future models. *EGU General Assembly 2021, EGU21‐7182, 10.5194/egusphere‐egu21‐7182, 2021*.

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Schmieder J., Hanzer F., Marke T., Garvelmann J., Warscher M., Kunstmann H. and Strasser U. (2016) The importance of snowmelt spatiotemporal variability for isotope-based hydrograph separation in a high-elevation catchment. *Hydrol. Earth Syst. Sci.* **20**, 5015-5033.

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