Author responses to Reviewer #3 (Comment on hess-2021-512)

1. This article estimates the role of glacial meltwater in generating stream discharge in three Alpine catchments located in the Central Swiss Alps. Stable water isotopes (2H, 18O) are used to quantify the proportion of streamflow generated from ice melt vs rainfall while electrical conductivity measurements are qualitatively used to understand the dominant hydrologic processes. The article concludes that ice melt is the dominant driver of streamflow generation in August and September and propose that due to climate change, glacial coverage will reduce which might adversely impact streamflow generation during this period of the year. The article then estimates annual glacial melt discharge in these three catchments and propose a power law relationship between minimum annual glacial meltwater discharge and the glaciated area, which can potentially be extrapolated to catchments with known glaciated areas.

The paper is well written but lacks significantly in terms of robustness of the methods used and the inferences made thereafter. The key problem that I see is one missing end-member which is "groundwater" that has not been considered in this article. In Alpine environments, groundwater has a significant role is sustaining streamflow during low flow periods in August-October period. In this particular case study, I think groundwater is significantly contributing to streamwater generation during August-September period as can be inferred from the high EC values during that part of the year (Figure 6C). If this period was completely dominated by ice melt originating from glaciers, EC values would be much lower and similar to that observed in the June-July period in Steinwasser catchment when snowmelt was dominating streamwater recharge (Figure 6C). As Steinwasser is the only catchment which has a longer timeseries of EC values, we can see that snowmelt was probably dominating stream recharge in June, July (low EC values) and then groundwater kicked-in in late August which is why EC values increased significantly. As the article has only relied on stable isotope measurements, this distinction is missing. I want to see if the results would be similar if the end member mixing exercise was undertaken with EC values and not stable water isotopic ratios. This also makes sense because electrical conductivity is largely a conservative tracer.

We thank reviewer#3 for these thorough comments. As mentioned in the general response to the reviewer's comments, we agree that our approach of neglecting groundwater as significant interim storage for glacial melt, rainwater, and snowmelt was somewhat simplified and that our dataset does not allow making strong quantitative statements regarding the glacial meltwater contribution to mountainous streams. Hence, we plan to slightly change the focus of the manuscript and we plan to address more the opportunities, challenges, and limitations of using stable water isotopes to quantify the contribution of glacial meltwater to mountainous streams

In addition, we agree that EC values are crucial to identify an important groundwater contribution to streamwater samples such as suggested by Reviewer #3. However, we somewhat disagree that the EC is a conservative tracer. This is because EC values are proportional to the sum of solutes dissolved in the groundwater. Solute concentrations in turn are mainly controlled by the overall degree of mineral dissolution reactions occurring in the subsurface, which for granitic systems is directly proportional to the subsurface residence time of the groundwater. Thus, because of this reactive behavior, groundwater EC values cannot be used to determine the contribution of rainwater, snowmelt and glacial melt in specific groundwater samples. Instead, EC values of streamwater samples can be used to quantify the corresponding groundwater component. However, this does not necessarily help in getting better estimates for the contributions of the rainwater, snowmelt and glacial melt endmembers in a specific streamwater sample because groundwater consists of the same three end-members.

2. In terms of mechanism, I think there might be significant subsurface storage that is getting recharged by snowmelt and ice melt (hence very depleted) and this storage is then recharging the stream during August September period. If this mechanism is indeed true, then the underlying hypothesis that rapidly retreating glaciers will lead to very low flows in August September period will not be true as groundwater can be recharged via rainfall, snowmelt and ice melt. I would like to hear the authors' perspective on this and if this was considered as a possible hypothesis.

Well, if the glacial meltwater contribution decreases then the discharge is much more sensitive to meteorological variations because they control the amount of snow and rainfall that is recharging and is stored in the groundwater systems. For instance, for dry years, the discharge will be much lower after the disappearance of the glaciers, whereas for wet years the lacking glacial meltwater contribution might be compensate by the contribution of stored groundwater originating from rain and snow melt water. This discussion will be added to the revised manuscript if we are allowed to revise the manuscript.

3. Variability in the isotopic ratio of ice melt (originating from the glacier) is very low and might not be very realistic. This is probably due to very limited ice sampling (only sampled two times in August and September, L418). Hence, the distinction in isotopic ratio of ice melt and snowmelt might be more of a function of sampling bias rather than any underlying hydrologic process.

We agree with the reviewer that the number of glacial melt samples is low. Nevertheless, since it has been previously shown that the isotopic variability of glacial melt is rather low, at least when compared to that of snow (Müller et al., 2021; Schmieder et al., 2018; Zuecco et al., 2019), 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.

4. L521-523: I find it very surprising that the ice melt contributes to ~25% of total discharge in Giglibach when the extent of glacial coverage is only 8%. On the other hand, the extent of glacial coverage is as high as 28% in Steinwasser but the contribution of glacial melt to total discharge is only slightly higher at ~29%. Are these estimates reasonable or to put it differently, have these kinds of number been reported at any other place where despite very high glacial coverage (>3x for Steinwasser compared to Giglibach), contribution to annual stream discharge only increases slightly.

As nicely pointed out by Reviewer #1, our estimations for the Giglibach catchment cannot be true. The erroneous quantification results from neglecting the groundwater contribution, which is much higher in the Giglibach catchment compared to the other catchments (see also general response to the reviewer's comments).

5. L377: Groundwater might also be a significant contributor to stream recharge. I propose the authors to explore this hypothesis

We agree with the reviewer. An extended discussion regarding groundwater will be added when preparing the revisions if we are allowed to revise the manuscript (see also general response to the reviewer's comments).

6. L381-385: If snow and glacial meltwater show lower EC compared, then August and September discharge cannot be explained by glacial meltwater as EC values are high across catchments

Theoretically, the August and September discharge could be related to glacial meltwater that has interacted with the minerals in the subsurface and thereby increased its solute concentrations and hence, EC values. In any case, groundwater flow is significant (but variable in the different catchments) and we fully acknowledge that we have to provide a corresponding discussion in the revised manuscript if we are allowed to revise the manuscript (see also general response to the reviewer's comments).

7. L418: Two samples is very few to make any meaningful statistical judgement

See the response to comment 3.

8. L420-423: Details about Gaussian error propagation has not been explained anywhere in the article. Additionally, ±2% uncertainty bound seems to be very small. This might be due to small sample size.

We agree that an uncertainty of ±2% is too low. This is mainly because we have neglected groundwater as a significant interim storage for rainwater, snowmelt and glacial melt. An extended discussion regarding the corresponding uncertainty for quantifying the glacial meltwater contribution will be added when preparing the revised manuscript.

9. L483-486: Has this been reported for the first time? I am not familiar with this literature, are there other studies which have reported similar results? In that case, it might be good to include relevant references.

As described in in the general response to the reviewer's comments, we plan to slightly change 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 discharge. Therefore, Figure 8 will be removed when preparing the revised version of the manuscript if we are allowed to revise the manuscript.

10. L544-545: Using temporally high-resolution isotope measurements leading to superior quantification of glacial meltwater hasn't been shown in this article

Temporally high resolution refers to snow and streamwater samples as pointed out in earlier replies. This will be clarified in the revised manuscript if we are allowed to revise the manuscript. In addition, we will delete the somewhat misleading statement that our data has led to an improved quantification of glacial meltwater contributions. Instead, we will emphasize that our dataset provides new insights into the opportunities, challenges and limitations of using stable water isotopes for such quantification.

11. L284: It should read as "… in the ablation compared to the accumulation period …"

Thank you for spotting this error. We will correct it accordingly in the revised manuscript if we are allowed to revise the manuscript.

12. L25: It might be clearer if its written as "… which has a heavier isotopic signature compared to the snow that fell during the accumulation period…"

Thank you for this nice suggestion. We will correct it accordingly in the revised manuscript if we are allowed to revise the manuscript.

13. L538: Should be “. This is of major importance ..”

Thank you for spotting this error. We will correct it accordingly in the revised manuscript if we are allowed to revise the manuscript.

14. Figure 1: Incorrect figure caption, Wendenwasser is shown in grey and not pink.

Thank you for spotting this error. We will correct it accordingly in the revised manuscript if we are allowed to revise the manuscript.

15. Figure 5: Should also include snowmelt isotopic ratios here to make the comparison between snowmelt and ice melt easier. Is this any reason to believe that both will have different isotopic signature?

We agree that it makes sense to merge Figure 4 and 5. This will make it clearer that the isotopic snow signature is strongly variable and hence, overlapping with the signature of ice. The variation is of the snow signature is likely caused by the moisture exchange with the atmosphere after snowfall. An extended discussion regarding this process will be added to the revised manuscript if we are allowed to revise the manuscript.

16. Figure 6: In subplots B, C and D there is a lot of whitespace due to very large y-axis bounds. For e.g. there are no discharge measurements below 0.1 m3/s, so showing y-axis values up to 0.01 m3/s is not necessary. Similar is the case for EC values < 10. I will suggest the authors to consider using tighter y-axis bounds so that the underlying data variability is more clearly visible.

Thank for this suggestion, we will certainly consider it when preparing a revised version of the manuscript if we are allowed to revise the manuscript.

17. Figure 6A: Is the unit mm or mm/hr?

Fig. 6A shows daily amounts of precipitation. The unit should thus be mm/d. This will be clarified in the revised manuscript if we are allowed to revise the manuscript.

18. Figure 7: I will suggest adding uncertainty bounds in this figure. Also, is 90%+ glacial melt contribution (Figure 7A) a plausible estimate at the end of July in a catchment which is only 6% glaciated?

As pointed out earlier, the estimates shown in Fig. 7a cannot be entirely correct because the Giglibach catchment is likely strongly affected by groundwater flow, which we have neglected as interim water storage. Adding uncertainty bounds is a good suggestion and we will consider this when revising the manuscript if we are allowed to revise the manuscript.

19. Figure 7 caption: Should be “.. glacial melt water contribution to the three ..”

Thank you for spotting this error. We will correct it accordingly in the revised 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.*

Schmieder J., Garvelmann J., Marke T. and Strasser U. (2018) Spatio-temporal tracer variability in the glacier melt end-member — How does it affect hydrograph separation results? *Hydrological Processes* **32**, 1828-1843.

Zuecco G., Carturan L., De Blasi F., Seppi R., Zanoner T., Penna D., Borga M., Carton A. and Dalla Fontana G. (2019) Understanding hydrological processes in glacierized catchments: Evidence and implications of highly variable isotopic and electrical conductivity data. *Hydrological Processes* **33**, 816-832.