

Response to RC1:

Overall, this is robust research presented in a well written manuscript. I was impressed with the thorough analysis you performed when comparing the simulated results to the in situ field data. You also produced clear visuals to report the results. I have some comments below in response to a few places in the paper where I thought you could add additional context.

Answer: Thanks very much for the helpful review and appraisal of the value of our work.

Introduction

A paragraph is needed introducing, explaining, and justifying the use of the Water Balance Simulation Model (WaSiM) as the hydrologic model for this study. Given that this research is the first to apply WaSiM in high-elevation environment, this explanation/knowledge gap should also be addressed in the introduction.

Answer: We will elaborate and address this matter further in the Introduction. We adopted WaSiM in this research because (i) WaSiM is one of the very few physics-based and fully-integrated hydrological models that enable to model both surface and subsurface in detail in glaciated catchments by updating the glacier geometry; (ii) such multi-variate, spatially-distributed, and physics-based modeling in both surface and subsurface potentially allows new hydrological process understanding and plausible flow and storage quantification, but it has been rarely done in high-elevation glaciated environments. More precisely, the novelty of this modeling work lies in being the first to apply a **fully-distributed, fully-integrated surface-subsurface** hydrological modeling approach using WaSiM, calibrated with extensive field observations (glacier, snow, river discharge, and groundwater), to address the key gaps in understanding hydrological process in **glacierized high-elevation** environments. We will make this point clearer in the Introduction.

Additionally, I think a paragraph is needed explaining how in situ data can be used in these fully-integrated models would be helpful – particularly by highlighting the rarity of in-situ groundwater data.

Answer: We agree and will enhance the elaboration on this aspect in the Introduction. Indeed, the current version lacks some general considerations and references about the challenge of using in-situ, point-scale data to constrain distributed models (scale-gap) and even more so in highly heterogenous landscapes. We will add this to the introduction with reference to snow heights, soil moisture and groundwater levels (the three most commonly used types of in-situ data for these models).

Study Area

Figure 1b – The basemap is present showing the Germany label cut off. I would recommend fixing your map.

Answer: Thanks for pointing this out. We will fix this issue on the map.

Section 3.2 You mention using the sen slope and Mann-Kendall test – please also add your p-value significance threshold, confidence intervals, etc.

Answer: We agree and will add these details in this section. We applied a standard p-value significance threshold of 0.05 and the 95% confidence interval.

Section 4.4.3 It seems to me that there should be additional statistical significance tests such as RMSE, MAE and p-values. I am recommending adding the RMSE and MAE analysis. Also, I recommend expanding section 4.4.3 to include the NSE, spearman rank correlation coefficient, and p-value thresholds that you considered “significant” in this analysis.

Answer: We agree and will add RMSE and MAE analysis to help evaluate model performance additionally. We also agree to include the NSE, spearman rank correlation coefficients, and the p-value thresholds (i.e. 0.05) that we applied to define “significant” in this analysis.

Line 368: please provide the river gauge and borehole ID 4479 water fluctuation in order to compare it to the 0.8 reported for the borehold ID 4478.

Answer: The water level fluctuation at the river gauge is 0.24 m, that at borehole ID 4479 is 0.26 m and that at borehole ID 4478 is 0.88 m. We will add these details to facilitate the comparison.

Line 565: I’m not sure that the hypothesis that “subsurface lateral flow may have limited contribution to streamflow generation at the high-elevation headwater landscapes.” Is fully explained in the introduction. Therefore, I would recommend ensuring that this narrative is present throughout the paper, including an additional explanation in the introduction. I’m also not sure how this is an “outrageous hypothesis” – perhaps expand on why this hypothesis is unusual for hydrologic research?

Answer: We agree and will add this hypothesis and explanation in the Introduction. In particular, we will refer the reader to the widely accepted runoff generation classification diagram by Dunne (Dunne, 1983; Trancoso et al, 2016) which states that in humid climates and steep slopes, runoff generation is dominated by lateral subsurface stormflow (in combination with saturation-excess overland flow). This hypothesis was framed as “outrageous”, as it can be controversial to the widely acknowledged hydrological process understanding that subsurface lateral flow plays an important role (20-60%) in streamflow generation (Gao et al, 2023; McGuire et al, 2024; McMillan et al, 2025). The experimental data and the model used to interpret them point to a different model which is consistent with the conceptual description of hydrological flow processes in high Alpine landscapes (Fig.1 in van Tiel et al. 2024), indicating the limited contribution of subsurface lateral flow to the headwater streamflow generation. Here we test this hypothesis by adopting a physics-based, spatially distributed, and fully-integrated surface-subsurface hydrological model, which enables us to quantify the role of subsurface lateral flow in the study site. We will expand on this and in particular emphasize the fact that dynamic groundwater response (baseflow variations) can explain much of the observed variability – a process that is not explicitly addressed in the most commonly adopted runoff generation classification scheme by Dunne (Dunne, 1983). We will also clarify that the WaSiM model enables the direct runoff (surface runoff)

to be generated by both mechanisms of saturation excess and Hortonian (infiltration capacity excess) runoff.

Conclusion: I think you can add a paragraph on how the findings of this research can be applied to similar high alpine ecosystems throughout the world in order to give the research a “global application”

Answer: We agree and will elaborate more on the applicability of the research findings in a global context, in particular also in relation to the above discussed “universally” accepted runoff generation classification scheme. As the first physics-based, fully-integrated, and spatially-distributed, surface-subsurface hydrological modeling study with WaSiM (in contrast to external coupling causing process disconnections), which explicitly considers groundwater time series for model calibration, the achieved new insights on hydrological process understanding should be further tested and confirmed in other high Alpine settings. The insights from this study are likely applicable to the mountain ranges with similar climatic, geological, and landscape settings and the sites with similar subsurface permeabilities, such as the central European Alps, Scandinavian Mountains, and Canadian Rockies. The high-elevation headwater catchments in these non-carbonate mountain ranges share key characteristics, where Quaternary sediments host shallow groundwater systems, impermeable bedrock restricts deep percolation, and subsurface lateral flow is often limited, especially in steep terrain. These are opposed to settings with distinct subsurface permeabilities, e.g. the Hindu Kush Himalaya or with very different climatic settings, e.g. the Andean Alps. Future investigations can refer to the demonstrated workflow and recommendations (Sec. 6.3) and potentially overcome the limitations (Sec. 6.4). Such global cases modeling and intercomparison contribute to a holistic understanding of hydrological processes in high Alpine environments.

References

- Dunne, T. (1983). Relation of field studies and modeling in the prediction of storm runoff. *Journal of hydrology*, 65(1-3), 25-48.
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- McMillan, H., Araki, R., Bolotin, L., Kim, D. H., Coxon, G., Clark, M., & Seibert, J. (2025). Global patterns in observed hydrologic processes. *Nature Water*, 3(4), 497-506.
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- Trancoso, R., Larsen, J. R., McAlpine, C., McVicar, T. R., & Phinn, S. (2016). Linking the Budyko framework and the Dunne diagram. *Journal of Hydrology*, 535, 581-597.