Detailed response to comments of Referee 1

Reviewer 1

I found the manuscript from Moradi and colleagues greatly improved after the introduced amendments. The story is more focused and presented, and the title aligns with the key findings. I more easily understood why did you addressed perennial ice melt as a key driver for solute export. Also, I now better got the relation between concentrations and solute export in your system.
In my opinion, the work is close to be suitable for publication after a round of minor revisions.

We thank Stefano Brigenthi for his time and effort in providing insightful and valuable comments, that helped with improving the manuscript.

Comment 1
My major suggestion is about the conceptual model figure. There (not in the text, where everything is clear to me), I cannot follow very much how does the water film develop, and how it is related to the seasonality of the solute export. The key difference with conceptual models illustrated in other works is the presence of water film zooming boxes, where however it is unclear how films develop and evolve. In my opinion, the figure would greatly benefit from having a total of three/four boxes, where you can more precisely illustrate: a) the development of solute-enriched water films related to past environmental conditions: b) present-days during early summer (snowmelt seepage and translatory flows into the aquifer enhancing bulk solute export at the spring); c) present-days during mid-summer (most snow disappears and the active layer thaws, water films start to be exported); d) present-days during late summer (permafrost degradation, water films are well-connected and the solute export occurs in the aquifer and during rainfall events).

Thank you for these helpful suggestions. We have updated the conceptual model (Fig. 8) accordingly and with a particular emphasizes in illustrating how water films can develop at the top of the rock glacier core throughout the monitoring period for a) the past and b) the current situation. Likewise, we have updated the corresponding figure caption.

Comment 2
Regarding these water films, were these previously found and investigated in other permafrost environments, or is it the first time that their occurrence is hypothesized/addressed?

We are not the first one mentioning the presence of liquid water within rock glacier cores. In the literature, it is well accepted that temperatures above zero and hence liquid water can occur in the sediment-ice mixture of rock glacier cores (e.g., Krainer et al., 2015; Jones et al., 2019, and references therein; Nickus et al., 2023), In the previous, commented version of the manuscript this is clearly stated on lines 425-428. Moreover, we use this temperature information to hypothesize that immobile, stagnant water, which is prerequisite for the accumulation of toxic elements over time, mainly occurs during colder climatic conditions or at high altitude. To do so, we describe such stagnant water as “water film”, which might be indeed a novel description for liquid water present in rock glacier cores. With the changes made to Figure 8 and the corresponding caption, this should be clearer now (see our response to Comment 1 above). To further address this comment, we have repeated that temperatures above zero may occur in rock glacier cores right before mentioning the term “water film” for the first time (see lines 444-445 of the revised manuscript).

Comment 3
Minor issues include:
• There is a mixed use of past and present tenses, I kindly ask you to check the consistency of verb tenses

Done. Now our results are consistently presented in past tense. In contrast, general statements are still written in present tense because this makes more sense.

Comment 4
• Are units with a fraction provided as “/” ok? Please check if the journal requires exponential notation (e.g., mg/L vs. mg L-1). Please ensure consistency in the text, tables and figures

All the units with fractions are written exponentially as of the Journal requirement. To address the comment, we have updated the axes labels of Figs. 3-8.

Comment 5
• Check the consistency of using Tab. Vs. Table and Fig. vs. Figure

Thank you for pointing out this point. The consistency has been checked and corrected if needed.

Comment 6
Other minor issues:
Lines 29 -31. I suggest first introducing what rock glaciers are, then mention their significant as water resources.

Thank you for the suggestion. These lines have been moved after the introduction of rock glaciers (lines 40-41).

Comment 7
Lines 38-39. I did not get what “glacial” and “non-glacial” in parentheses mean, is it glacial vs. permafrost origin?

We agree that these terms caused confusion. Therefore, we have revised the corresponding sentence (lines 37-38).

Comment 8
Lines 68-70. Please mention the potential importance of microbial activity, that can catalyse chemical reactions and speed-up sulfide oxidation rates (Parbhakar-Fox and Lottermoser, 2017; https://doi.org/10.1007/978-3-319-42731-7_2). Also, cryophilic microbes are present in the interior of rock glaciers (Williams et al., 2006; DOI: 10.1002/esp.1455; Sannino et al., 2021).

We agree that microbial activity may promote mineral dissolution reactions although we have no information if this is relevant at temperatures around the freezing point of water such as in the studied rock glacier. Nevertheless, to address the comment we have added the potential of microbial activity in enhancing sulfide oxidation rates (lines 66-67).

Comment 9
Line 80. Can you briefly build on other studies at high elevations that investigated bulk solute fluxes (e.g., from glaciers)? See e.g. https://doi.org/10.1002/hyp.5812 and 0.1002/hyp.1041 and https://doi.org/10.1016/j.apsoil.2021.104079

On these lines, we mainly discussed solute fluxes from rock glaciers whereas the suggested studies relate to other hydraulic units. In our opinion, adding such discussion would dilute the key points of our manuscript, which was one of the main criticisms in the first round of reviews. Therefore, we prefer to keep the focus on rock glaciers and no change was made to the manuscript.

Comment 10
Line 95. Can you provide more information about the rock glacier (e.g., size, elevation range)? Perhaps it would be good to also give it a name, instead of referring to the “rock glacier illustrated in Figure 2” all over the text?

The size of the rock glacier and the elevation of its springs has been described on lines 98-99 of the previous, commented version of the manuscript as well as in the following paragraph. The rock glacier does not have a name. To address the comment, however, we have replaced the term “rock glacier illustrated in Fig. 2” to “the studied rock glacier. Moreover, we have added the elevation range (lines 98-99).

Comment 11
Line 445. Even if this would be the key connection between permafrost ice melt and solute export, the occurrence of this water film is not well introduced in my opinion. I suggest adding, after the sentence at line 444, something like: “We hypothesize the existence of a water film occurring in the rock glacier interior and related to the solute export from the landform…”

We do not hypothesis that liquid water may be present in rock glacier cores. In our opinion, this is fact because temperatures above zero (causing melting of ice based on physical laws) have been previously reported to occur in rock glacier cores in late summer (Krainer et al., 2015; Jones et al., 2019, and references therein; Nickus et al., 2023) (lines 425-428 of the previous, commented version of the manuscript). Nevertheless, to address the comment we have updated Figure 8 as well as the corresponding caption (see response to Comment of Reviewer 1) and we have repeated that temperatures above zero occur in the rock glacier core in late summer right before mentioning the term “water film” for the first time (lines 444-446, see also our reply to Comment 2 of Reviewer 1).

Comment 12
Line 467. perhaps you can refer to as translatory flow mechanisms, even though others like fill-spill and fill-spill-drain were highlighted in previous studies (e.g., Harrington et al., 2018; https://doi.org/10.1002/hyp.13248). Displacement (translatory flow; see Sprenger et al., 2019; . https://doi.org/10.1029/2018RG000633) and/or uplifting mechanisms (e.g., transmissivity feedback; Bishop et al., 2004; . https://doi.org/10.1002/hyp.5209) have been suggested as key processes promoting the outflowing of “old” groundwater during rainfall events in aquifers and have been also suggested to occur in periglacial taluses (Muir et al., 2011; 6. https://doi.org/10.1002/hyp.8060) and rock glaciers (Brighenti et al., 2021; DOI: 10.1002/hyp.14159).

Thank you for this suggestion and all the interesting references. In our opinion, however, an extended discussion of the multiple terms (there are more than those mentioned by the reviewer) previously used to describe the mobilization of “older” groundwater during rainfall events is beyond the scope of this manuscript. Moreover, we think that it would dilute the key points of our manuscript, which was one of the main criticisms in the first round of reviews. Therefore, no change was made to the manuscript.

Comment 13
See following sections and the pdf file where I added further suggestions.

Thank you for these additional suggestions. We went through the comments in the pdf and we have implemented essentially all of them (see tracked changed version of the manuscript), except those also mentioned in Comments 9 and 12 above. In addition, we applied minor grammatical changes.

Detailed response to comments of Referee 2

Reviewer 2

I thank the reviewers for taking on board all of my comments and suggestions - I can see that these changes have been made to the manuscript, and the has significantly improved in its structure, narrative and content. I just have two minor technical corrections to request from this revised manuscript:

We sincerely thank the reviewer for their insightful feedback, which greatly contributed to enhancing the quality of the manuscript.

Comment 1
Can AP1_2 be labelled in Figure 1 in green to make this clearer? The green dot has been added, but no label, so it is not clear to the reader that the green dot is AP1_2 until the read further into the figure caption.

There is an “AP1_2” label for the green dot in both Figures 1a and 1b. Maybe there was a technical problem that this label was not visible for you.

Comment 2
Figure 1 caption also mentions a red triangle, which is not visible?

The red rectangle also exists in Figure 1a, which shows the studied rock glacier. Maybe there was a technical problem that this rectangle was not visible for you.

Comment 3
"Sta Maria-Munstair" -> should this be St. or Station not Sta?

“Sta Maria” is abbreviation for a small town called “Santa Maria”. To avoid confusion, the complete name “Santa Maria” is used in the figure caption.

Comment 4
Figure 1 shows the yellow precipitates in stream in 1a only, so it might be worth clarifying this in the Figure caption too where it is referred to (towards the end).

Thank you for the suggestion. However, instead, the section with yellow precipitates is now highlighted in Figure 1b as well.

Comment 5
Figure 8 caption:
The new figure caption for Figure 8 is extremely long - is all of this information required, is there a way to make this more concise?

In our opinion, most of the information is required to understand the key points of the figure without reading the text. Nevertheless, to address the comment, the last two sentences were deleted because they essentially represented a copy from the main text. Moreover, based on Comment 1 of Reviewer 1, the figure and its caption were update to improve the clarity of the figure.

References

Jones, D. B., Harrison, S., Anderson, K., and Whalley, W. B.: Rock glaciers and mountain hydrology: A review, Earth-Science Rev., 193, 66–90, https://doi.org/10.1016/j.earscirev.2019.04.001, 2019.

Krainer, K., Bressan, D., Dietre, B., Haas, J. N., Hajdas, I., Lang, K., Mair, V., Nickus, U., Reidl, D., Thies, H., and Tonidandel, D.: A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy), Quat. Res. (United States), 83, 324–335, https://doi.org/10.1016/j.yqres.2014.12.005, 2015.

Nickus, U., Thies, H., Krainer, K., Lang, K., Mair, V., and Tonidandel, D.: A multi-millennial record of rock glacier ice chemistry (Lazaun, Italy), Front. Earth Sci., 11, https://doi.org/10.3389/feart.2023.1141379, 2023.