Author's response

We would like to thank both referees for their constructive comments and feedback on this manuscript.
We think that the suggested revisions based on their comments has certainly improved the article. Please find our responses (in blue) to the main points raised (shown in black) below.
Here are the main improvements reported:

- On the counterfactual analysis, we replaced table 1 with a dedicated figure, expanded the related text to make it more impactful.
- We provided further information on the albedo sensitivity analysis in the methodology, results and in the limitations sections.
- We thoroughly revised the discussion section, referring to other studies, highlighting the peak glacier water concept and referring to the implications on water management.

Reply to referee 1

General comments

1. You should discuss the sensitivity of the glacier melt contribution to your ice albedo value and glacier-melt initiation threshold value. Since this is the main result, there needs to be some quantitative uncertainty or sensitivity analysis performed and reported.

→ Thank you for your suggestion. We added information on the sensitivity of glacier melt contribution with respect to the different albedo values tested and reported in Figure 2 in methodology section (section 2.3 Simulation set up) and in the result section 3.1 (Glacier module performance). Moreover, we expanded the text in the Limitations section 4.1 so to provide further information on the simple dynamic glacier module of the semi-distributed hydrological model we used, and the limitations in capturing multiple processes, such as increased melt rates due to accelerated fragmentation or to debris-covered ice, that influence melt dynamics in comparison to other models.

2. The discussion section needs to be more impactful. You should expand on the implications of your findings, especially as they relate to water availability and needs in the Adige. What are the water management implications? What are the consequences of lower glacial melt contributions to streamflow in the future? How might this change with predicted temperature and precipitation shifts in the region? You can also expand on how your results in the Adige fit into regional patterns, or how they compare to other similar basins. Right now, the discussion reads somewhat as an extension and summary of the results, but it should highlight the impact of the results.

→ We thoroughly revised the discussion section so to avoid repeating results and highlight the peak glacier water, water management implications as well as providing an outlook on future conditions and potential consequences.

3. It might be helpful if you framed part of your analysis/ discussion around distinct stages of glacier runoff. The fact that 2022 had lower melt than 2003 despite similar warm temperatures is a possible indication that the basin may have passed its “peak water” or peak glacier melt runoff (Huss and Hock, 2018). Using this terminology or a different, distinct glacier stage framework might provide a clearer lead-in to a discussion on the broader implications of your results.
    - Huss, M., Hock, R. Global-scale hydrological response to future glacier mass loss. Nature Clim Change 8, 135–140 (2018). https://doi.org/10.1038/s41558-017-0049-x

→ Thanks, and we referred to the peak water concept in section 4 when discussing the overall results and the implications for future water management.

Line-by-line:

4. Lines 23-24: In your results section, you mention KGE values between 0.4 and 0.86 (lines 241-242). There seems to be a mismatch between what is reported in the abstract and what is reported in the results.

→ Thanks and the reported values are correct. In the abstract, we added “for the whole upper Adige River basin at the Bronzolo closing station” so do make it different with the values reported in lines 271 (of the track change manuscript version) referring to the single subbasin units.

5. All sub-basins should be defined (perhaps in Figure 1), and you should explain what information about each sub-basin is available in your supplementary table. You reference basin numbers and some sub-basin names, but it is not very clear where they are located.

→ Thanks, we added the sub-basin border layer to Figure 1 for the 16 subbasins used in the calibration and validation. Moreover, we corrected a typo on the number of overall subbasins and added a map with the 61 subbasins used for the simulations (Figure S1) providing their id number and sub-basin macro-area names (Table S2) in the Supplementary Material so to provide further information to interpret the subbasin locations.

6. Line 140-141: What is the threshold value? Also, is it a threshold of depth (mm of SWE) or a percentage of area? This seems to be a very important parameter, but it is not described in much detail.

→ We added information on the minimum SWE value of 5 mm below which glacier can start melting referring to the paper from Zaramella et al., (2019) where it is proposed.

Zaramella, M., Borga, M., Zoccatelli, D., and Carturan, L.: TOPMELT 1.0: a topography-based distribution function approach to snowmelt simulation for hydrological modelling at basin scale, Geosci. Model Dev., 12, 5251–5265, https://doi.org/10.5194/gmd-12-5251-2019, 2019.

7. Figure 4: Remove light-colored boxes around panels.

→ we removed the boxes around the panels.

8. Line 285: r=0.47 is not a strong correlation; it is a modest correlation.

→ thanks for pointing it out and we replaced “strong” with “moderate” accordingly.

9. Line 307: You need to be more specific here. This year was the lowest for each of the 14 subbasins or overall, they have the lowest average SWE?

→ thank you and we modified the sentence so to make it clearer.

10. Section 3.3.3 should go in the discussion section and needs more description on the importance of glacial retreat to water resource availability.

→ thank you for your comment and based on your and the comments from reviewer n2 we kept section 3.3.3 as part of the results, expanded the related text, replaced table 1 with a figure (Figure 6) so to make this section more prominent adding further reference to it in the discussion section.

Reply to referee 2

General comments

11. There are many grammatical and writing errors in the current version of the manuscript. I have highlighted some of them in the specific comments section of this work,but have not listed them comprehensively. I recommend the authors conduct a close reading to improve the clarity of the writing, even in places with no scientific comments.

→ Thank you and we have gone through a language check.

12. I recommend that the authors re-structure the introduction. As it stands, it reads
    - the 2022 European/Italian alps drought
    - glacier shrinking in Europe
    - knowledge/modeling gap related to glacier modeling and glacier inclusion in hydrologic models
    - the 2022 drought again
    - what this study does

    I would like to see a structure that more methodically frames the impact of this study, which I see as an accounting for the presence or lack of glacier buffering of droughts in several important drought years. To me, this would start with an explanation of glacier-driven hydrological buffering, then the argument that this may be lessening due to glacier shrinking, then that modeling is required to understand how much buffering occurs (and any technological gaps that might be related), then an introduction of the domain of this study (the 2022 Alps drought).

→ Thank you for your comment. We implemented targeted modifications in the first part of the introduction so to avoid referring to the 2022 drought. We decided to keep a funnel structure starting from general sentences on droughts and glacier contribution and shrinking in Europe while keeping the hydrological-related part afterwards (lines 60-77). We think that this structure provides a general introduction being comprehensible to audience from many disciplines and smoothly move into more specific information to this study.

13. For the ICHYMOD-TOPMELT model: this seems to be an interesting and important application of this model. The discussion of the model does not make it clear which components were developed in previous work and which components are novel in this paper. Please make this more clear, which will also highlight the novelty of this work!

→ thank you, we changed the title of the dynamic glacier module so to stress that it is the novel addition to the hydrological model as it is also stated at the beginning of section 2.2.1.

14. Albedo calibration: There should be, at minimum, a sensitivity analysis performed on the albedo calibration, and more justification of choosing a singular albedo value. The resulting albedo value should be externally validated in some way (i.e., establish that the value is a reasonable value for glacier per the literature, observations, etc.) It seems that the results are moderately dependent on this value, but it is calibrated on only two individual observations and is held to be one singular value for all times of the year in all years. If such a calibration is required, all of these should be carefully justify ed. The choice to calibrated on albedo and not another parameter should also be justified.

→ thank you for this comment and we see added information in section 2.3 (lines 199-200 of the track change manuscript version) and section 3.1(lines 242-245) and in the limitations in section 4.1 (lines 500-519) so to clarify the conditions used to reconstruct glacier dynamics within the lumped hydrological model.

15. Focus on justifying all claims: The major point of this work is to quantify the role of glaciers in buffering/exacerbating hydrological droughts. I see opportunities to strengthen this argument with minimal analysis related to what you currently show and to focus more on this point than on a general accounting of drought conditions (which has been done in some of the literature in this region). Specifically, with your current counterfactual runs, can you present results on how much more buffering would have been provided if the glaciers had not retreated? I think that is the point of the counterfactual, but I do not see this result communicated very clearly. For example, there are currently 2 figures on the hydroclimate of drought, but the counterfactual, which I find more impactful, is a table that receives minimal discussion. What about a timeseries of streamflow showing the observation and then the counterfactual model? The discussion mostly focuses on the difference between dynamic and static, not on the use of the 1997 glacier area counterfactual, which I see as the more impactful result!

→ Thanks for the very useful comment. We have expanded the text on counterfactual and replaced the current table with a dedicated figure with info on runoff, glaciermelt and the glaciermelt contribution to runoff for the three major droughts considered. Moreover, we expanded the part on counterfactual within the discussion section.

Specific:

16. Use “significant” not “significative” and always include a statistical justification of “significant” when using. Otherwise, use another word, like “meaningful,” “observable,” or “large”

→ thanks we corrected it throughout the manuscript

17. L26: droughts (plural)

→ thanks, we changed it.

18. L28: using SWE acronym without first defining it

→ thanks, we have defined it already in the abstract as well as in line 134 (of the track change manuscript version) when it is introduced for the first time.

19. L29-30: Sentence “By contrast…” is written unclearly, please rephrase

→ thanks, we rephrased it into “By contrast, the significative runoff deficit in 2005 was driven by colder temperatures, which reduced glacier melt contribution to 4.85%, combined with low SWE conditions.”

20. L31: maybe “in contrast to” instead of “differently”

→ thanks we modified it accordingly

21. L34-35: be clear over what region you make this claim

→ we left the reference to “the upper Adige River basin” in the sentence as it was already stated.

22. L35: is the dependence showing a decreasing trend or are precipitation and snowmelt? Rephrase to make this clearer

→ We modified the sentence into “Glacier retreat is weakening the contribution of glaciers to summer flows, increasing the upper Adige River basin’s dependence on precipitation and snowmelt, the latter of which is also showing a decreasing trend”.

23. L51: grammar corrections to “39% of European glacier [is this count? mass? Area?] was lost”

→ thanks for pointing it out and we added reference to the “glacier mass” in the sentence.

24. L53: “recession” singular

→ thanks, we modified it.

25. L56: grammar corrections

→ we modified it as follow: “Yet, understanding glaciers’ contributions to buffering river streamflow during droughts remains limited and poses a major barrier to improving present and future water management.”

26. L73: This is the second portion of the introduction that introduces the 2022 drought – please restructure the introduction to have this information in one place

→ thanks, we modified the introduction as described in comment n.12

27. L75: clarify if the Adige River Basin is part of the Italian Alps (and therefore an example of the broader context you are describing). Refer to figure 1 here

→ Thanks for pointing it, we added “in the Italian Alps” and added reference to Figure 1.

28. L111: give the streamflow gauges a density too? #/length of river?

→ we added the value of density of (1 per 23 km of river) for the streamflow gauges.

29. L112: citation or link, not hyperlink

→ we added the link in brackets as suggested.

30. Figure 1: the lake and glacier colors are extremely similar and the lakes and glaciers are quite small so it is difficult to tell them apart

→ thanks and we made the glacier color brighter so it’s easier to distinguish them.

31. L140: should this be “lower, fixed albedo” ? -- how would a high and fixed albedo enhance absorption and accelerate melt?

→ thank you, this is a typo and we have changed “higher” into “lower”.

32. L157: why is n=3?

→ We added information on the value adopted in glacier modelling following the formulation of Farinotti et al. (2009) and Huss and Farinotti (2012).

33. L184: is the glacier albedo calibration a standard practice in this modeling? To me, this seems like a huge range of potential albedos that could have a massive impact on the results – what measures were taken to ensure that the calibrated albedo matches real albedo of the glaciers at this time (especially given the fact that we have spaceborne albedo estimates for many of these regions during this timeline).

→ Thank you, as for comment n. 14, we modified the methodology section 2.3, section 3.1 on results as well as the limitations in section 4.1 so to clarify the conditions used to reconstruct glacier dynamics within the lumped hydrological model.

34. Figure 2: What is the time interval for plotting the area of the glacier? If it is relatively coarse, use markers to show when the data points appear. If it is very fine, I am surprised to not see seasonality in glacier area – can you explain why this does not appear? Would there not also be a moderate amount of seasonality in overall albedo?

→ we considered yearly time interval since the update of the glacier extension works at a yearly scale. We added lines dots and x-axis ticks to highlight it in figure 2.

35. L206: why SWE at the end of June? This seems to be an unusual choice, given that significant melt occurs earlier in the spring. (April and May)

→ Thanks for this observation. We considered the end-of-June SWE since it represents the remaining snowpack just before the main summer melt season (July–September). We chose this metric as a proxy for the snow available to contribute to summer runoff; in alpine catchments, the snowpack by late June is critical for sustaining flows into the dry months.

We added additional information in line 224 with reference to the work from Penna et al., (2017), who investigated a similar contribution in a nearby area and showed that this period captures the snow influence on summer hydrology.

Penna, D., Engel, M., Bertoldi, G., Comiti, F., 2017. Towards a tracer-based conceptualization of meltwater dynamics and streamflow response in a glacierized catchment. Hydrol. Earth Syst. Sci. 21, 23–41. https://doi.org/10.5194/hess-21-23-2017

36. L230-233: the mean includes the years with positive change (unless you excluded them from the mean?) I think you mean here that qualitatively, there is minimal deviance from the long-term linear trend in any individual year (overall the signal is monotonic and linear), but that there are a few exceptions.

→ yes, we included also positive changes and computed a mean value to highlight the monotonic negative trend. In the last 30 years, a positive glacier mass budget happened for only very few years and glaciers.

37. Fig 3 caption: clarify in the caption that the increase is specifically the increase when making the glacier model dynamic.

→thanks and we added explicit reference to the static and dynamic glacier modelling modules within the caption.

38. Fig 3: If there are 65 subbasins in this study, why are most of them not included in this figure?

→ thank you for pointing this out. We performed hydrological simulations considering 61 (instead of 65, there was a typo) hydrological response units (stated in lines 190 of the track change manuscript version) and we parametrized the hydrological kernel of the hydrological model at 16 stream gauges (lines 182-183). For this reason, Figure 3 only reports the 16 subbasins and additional information on the 65 subbasins is reported in the Supplementary Material.

39. L266-269: cite for “previously identified” Also, this is discussion/conclusions, not results

→ we decided to remove this part as it was already reported in lines 280-284 (track change manuscript version).

40. L285-286, 292: 0.47 and 0.55 are not “strong” correlations – they are moderate

→ thanks and we corrected it.

41. Section 3.3: this is an interesting section on the hydroclimate drivers of melt, but it is not clear how this is related to the overall message of the paper, which is on modeling the contribution of glaciers to buffering (or not) droughts. For example, some of these topics are explored for the same years and regions in Brunner et al., 2023 (see fig. 4). It is also somewhat unclear from this section (and the corresponding methods section 2.5) which of the values used are from the model and which are from observations/reanalysis.

→ thanks for your comment. All analysis of hydroclimate drivers are based on simulation outputs and contributes to a better understanding on how past major droughts unfolded and the buffering role of glaciers. The purpose of this section is to understand the which patterns of hydroclimatic conditions characterized the most severe past droughts and led to the maximum buffering effect of glaciers to alleviate them.

42. The following section on counterfactuals is much more related, and, in my opinion, more novel.

→ thanks and we agree there is high novelty in the counterfactual analysis, and we have expanded and added a new Figure.

43. Figure 5: please change the color scale to something more intuitive on all graphs. As currently presented, the same color can have a different meaning (and different unit!) about the same variable in different columns. Further, some rows have diverging colormaps for both the value and anomaly while others do not, regardless of whether or not the quantity is diverging. I recommend picking non-diverging colormaps for each quantity, and then a different, maybe even standard between all variables, colormap for the anomalies. Also, improve the coherence of meaning between variables. For example, white currently means a high amount of runoff, a low amount of glaciermelt, and a medium temperature.

→ thank you for this comment. We changed them using different color palette for different variables as well as using non-divergent color palette for climatology (columns on the left) and divergent color palette for anomalies. We are aware that some inconsistencies are still in place, such as the white color means zero in each row. Nevertheless, we opted to have a color palette in each row so to provide a consistent scheme for each variable and we have selected different color palettes with "warm" colors for "dry" conditions and "colder" colors for wet ones.

44. Discussion: avoid repeating the results directly, but rather reference them (by figure, table, or section) and then explain the meaning. There should be more citations throughout this section as well, whenever comparing to a prior publication.

→ thank you and we modified the discussion section, adding more literature, considerations on the implications of our contrafactual analysis on the “glacier peak contribution” and our modelling approach limitations.

45. L384: reference where this is shown in the results

→ we added reference to figure 5

46. L435: Suggest completing the public release concurrently with this paper. Available by request does not satisfy open science guidelines, if this is what you are pursuing.

→ thanks for pointing this out, as not all the used code is available yet, we kept the availability of sharing data but removed the one on code.