Dear Editor,

We thank you and the reviewers for assessing our manuscript. We have revised the manuscript carefully to address all of the points and recommendations provided by the reviewers.

In summary, we have:

- added a table with a data overview of all datasets used in this study,
- designed a flowchart figure that illustrates the glacier mass balance extrapolation procedure,
- included several background figures in the supplementary information,
- restructured the results section, and
- added clarifications to the introduction, data, methods, and results sections.

We think these changes have strengthened the clarity and overall quality of the manuscript. Below you can find the responses to the reviewers comments. The table indicates in the first column the respective section the comment refers to, in the second column the reviewers comments and in the last column our replies.

We look forward to your feedback.

On behalf of all co-authors,

Marit van Tiel

	Reviewer	**Authors reply**
General	Dear authors, please find attached a PDF with detailled comments. I see the paper, with its focus on the buffering role of glaciers on streamflow in the 2022 extreme event, as important and meaningful contribution to a wide audience. The paper is well-structured and provides a huge and comprehensive amount of information across the Switzerland and a wide set of variables and plots are already well-thought and presented. Nevertheless, I think the manuscript could be further improved and clarified, not only content-wise but also language-wise. I had the impression that some descriptions and explanations of the plots could be improved and are rather vague or not precise enough making it hard to get an idea to which of the many details in the plots the authors are referring to. This facilitates misinterpretation and the mixing of numbers.	We are glad to hear the reviewer recognizes this manuscript as an important contribution to a wide audience and we thank the reviewer for the positive feedback on the structure and comprehensiveness of the paper and its analyses. We took the feedback on improving the clarity, both content- and language-wise onboard, to avoid misinterpretation and the mixing of numbers. We thank the reviewer very much for pointing out the various instances where improvements are needed. We reply below to each of the major comments, and added where needed the comments of the annotated pdf.
Methodological clarifications	Some major methodological clarifications that are necessary for the readability and comprehensibility (especially the glacier mass balance interpolation and adjustment). A flowchart like Fig. S2 is highly needed in the main text for the flow of the paper.	Please see our various replies below. We have added a flowchart figure in the revised manuscript (new Fig. 2) and added a table with an overview of all the datasets that were used (new Table 2). We added them here in the response (below this reply table).
More focus on hydro-meteorological conditions of 2022	Stronger focus on the hydro-meteorological conditions (also better represented in the main text rather than in the appendix) with some spatially-distributed water balance anomaly information.	We shortly summarized the hydro-meteorological information at the start of the results section (L260-266 new version): *With respect to the 1991-2020 period, the summer temperature anomaly in 2022 for the various catchments ranged between +1.8 and +2.7 °C. At a monthly scale, especially, May, June and July stood out, with monthly temperature anomalies of +3°C. Annual precipitation amounts were 17 to 40% lower than the reference period, with the highest deficits for catchments in the Po basin (Figure S6 & S7). The winter period was most exceptional with deficits up to 50% for catchments in the Po basin. Catchments in the Rhine basin showed the smallest deficits in winter, ranging between 20-35%. These meteorological conditions resulted in strong glacier mass losses (Table 3).*

		Furthermore, the introduction already included a description of the exceptional hydro-meteorological conditions of 2022 (L16-28). The glaciological and hydrological conditions are the subject of this paper and are presented in the results. The water balance anomaly information is already included in Figure 3 and we would like to keep this figure as it is, as it directly shows with the size of the bars how this compensation role of glaciers work. We have added the spatial version (maps) of the water balance anomalies in the SI, Fig. S7, see Figure R1.4 below, and refer to them in the main text.
	More emphasis on the methodological & dataset decisions and thus the error term provided in the context of the glacier compensation introduction	We added a data table overview to the revised manuscript (Table 2) and clarified what the error term in the calculation of the compensation level means: *Since it is not known which component causes the ϵ to deviate from zero, the term was once added to the surplus glacier melt component (ΔG, and once to the water deficit drivers (ΔP ($+\Delta S$) $-$ ΔET) in equation 4 to calculate the uncertainty in L. Depending on the sign of ϵ, it can refer to an over-/underestimation of (one of) the respective water balance anomalies or it could relate to water transfers from or to the catchment, affecting ΔQ in equation 5. Thus, in total, we derived three estimates of L per catchment, indicating the maximum range of possible values. (L240-245)*
	Weaknesses in the presentation of 5.4	We splitted 5.4 into three sub-sections, where the first section focuses on the long-term perspective, the second one specifically on the comparison of 2003 and 2022, and the third one on the changing sensitivity.
	Recommendations for extensions/replacements	Thank you for pointing these out – we reply to them here below.

PDF REMARKS

	Reviewer	Author reply
Abstract	"In contrast the relative contribution of glacier melt to streamflow stayed constant.." ⍰ Also compared to the other extreme years, meaning other hydrological droughts still had less streamflow reductions compared to 22?	Yes, indeed. For brevity we cannot repeat "compared to other extreme years", but we change into "stayed *rather* constant" to highlight the contrast and dependence on the previous sentence more.
	"Comparing 2022 to 2003 – the most comparable recent extreme summer- shows a declining glacier	The numbers are 2022 based not 2003 ⍰ we simplified the sentence:

	meltwater supply for 55% of the catchments during summer and 36% during July, despite more intense melt, with the difference in summer/July reflecting the extremeness of the melt conditions, counterbalancing the reduction in glacier area." I think this sentence would highly benefit to split it into 2. Besides, I would recommend saying "Compared to 2022, 2003 that has been the most recent comparable/similar...". Moreover, I would recommend making the "more intense melt" part could benefit by adding again that specific (per unit area) rates are meant (at least this is how I understand it), otherwise it reads very contra-intuitive with the 55% decrease and might confuse readers.	*In 2022 versus 2003—the most comparable recent extreme summer—total glacier meltwater supply decreased in two thirds of the catchments over the entire summer, and in one third in July. In the remaining catchments, the more intense specific melt of 2022 could offset the 21% glacier area loss since 2003.*
Introduction	I of course agree that the vast majority of studies (which is indirectly stated when reading the remaining Introduction), the authors should add a paragraph that focus on the actual topic of the manuscript: buffering capacities/roles of glaciers in extreme years, which is missing at the current stage. However, there is definitely related literature.	We added some more references to the paragraph before that discussed the role of glaciers in extreme years and added this sentence to the introduction (L40): *Beyond merely buffering drought, glaciers can counterbalance some of the precipitation-driven water deficits by releasing more meltwater than normally during heatwaves (Van Tiel et al., 2021; Anderson and Radic, 2023). For example, Zappa and Kan (2007) showed that during the 2003 drought and heatwave in the European Alps, catchments between 10-20% of glacierization showed positive streamflow anomalies, despite strong precipitation deficits. Besides the role of catchment glacierization, a detailed quantification of this counterbalancing effect of water deficits at regional scales is lacking. Such a quantification is crucial to understand the diminishing role of glaciers for mitigating hydrological droughts.*
	Drought term never properly introduced, and are you talking about meteorological drought or hydrological drought. Suggestion to make a section on hydro-meteorological conditions and providing maps with color coding	We added a drought definition in the introduction ("a sustained and regionally extensive period of below-normal water availability"). We refer both to meteorological and hydrological droughts. More specifically the paper analyzes how glaciers can alleviate the propagation from a meteorological to a hydrological drought. Thus, the term "drought" encompasses the situation in Switzerland in 2022 where it was extremely dry due to a lack of snowfall in winter, rainfall in summer, impacting streamflow and glacier melt.

		As indicated before, we have summarized the hydro-meteorological conditions of 2022 in the introduction, at the start of the Results section and provided maps of the water balance anomalies in the SI (Figure S7), to avoid overlap with information already shown in Figure 4 in the main text.
	What I am additional missing in the introduction (with respect to what I have said before already) is to provide context for some previous extreme yers in the Alps. I believe that there might be studies that evaluated extreme conditions and especially some of the years later chosen by the authors?	In the revised version, we added some references that studied the extreme year 2003 in the Alps (Zappa and Kan, 2007; Koboltschnig and Schöner, 2011).
Hydrological, Meteorological and cryosphereic data	Add basin area to table 1	Thank you, this has been added to the table.
	Figure 1 – add a legend for the basin colors	We have added a legend for the basins and changed the color of the glacier outlines on the map.
Methods	Add a flowchart for the methodology (glacier part) or a table with an overview of all the data	See reply above. We added a table with all the data in section 3 and added a flowchart in the methods section to better illustrate the glacier mass balance interpolation procedure. See the additional Figure (R1.1) and the Table pasted into the response letter below.
	Explain reason for 2011-2020 reference period for the glacier interpolation method	Whereas the reference period used in the study (1991-2020) was used as a climatological baseline, another period was needed for deriving the glacier mass balance as the data for most glaciers does not cover this full 30 year period. Thus this 10-year (2011-2020) reference period was chosen to optimize the number of glaciers for which their measurement period covers this period. For explanation, we added in the manuscript: *This glacier reference period was chosen to optimize mass balance data availability (Section 3) (L143-144)*
	Why where actual values and not anomalies used for the winter mass balance extrapolation?	There are two reasons for this decision: 1) absolute winter mass balances are assumed to vary less in space than annual mass balances as this is purely the accumulation term without glacier dynamics involved. 2) For long-term average winter mass balance, no glacier-specific information is available as for the annual scale (based on geodetic surveys). Therefore, using anomalies is not possible for the winter mass balance term. This aspect is now explained in the manuscript:

		Observed winter mass balances ($B_{w,g,y}$) were extrapolated based on their actual values (instead of their anomalies) because no long-term average winter mass balance is available for each glacier and Bw is expected to vary less in space as no glacier dynamics are involved here (L153-155)
	Literature or proof from the data why higher glaciers receive less accumulation?	The relation between median glacier elevation and precipitation is directly given by the dependence of air temperature on elevation: We can assume that temperature at a given elevation throughout Switzerland is similar. A glacier with a high median elevation thus must be characterised by less precipitation as melt rates are smaller (lower average temperature). This has already been shown e.g. by Ohmura et al. (1992) and is also evidenced by plotting observed winter mass balance data of Swiss glaciers against their elevation (see SI Fig. S3) and here in the response (Fig. R1.2) In the revised paper, we added this reference and point towards Fig. S3 *To reflect the differences in amounts of snow accumulation for individual glaciers due to their characteristic location, a correction factor was applied to each extrapolated winter mass balance value. This factor is based on the difference in median glacier elevation of the respective glacier with the surrounding glaciers. Glaciers at higher elevations than their surroundings receive a negative correction (wind-erosion processes), while glaciers located lower than their surrounding glaciers receive a positive correction (snow-deposition processes) (Ohmura et al., 1992) (Fig. S3).*
	Correction of anomalies to Bgeod is not clear	Since the Bgeod (1980-2010) and the mass balance anomalies (based on 2011-2020) do not refer to the same period, this difference needs to be accounted for. Therefore, we calculate the mean of the 1980-2010 anomalies (based on the ref period 2011-2020) and subtract this from the calculated anomaly. This way, the mean of the annual mass balances for the period 1980-2010 agrees with the geodetic mass balances, while the annual mass balance observations are used to determine the temporal variability. We revised the corresponding text slightly: *"Here, $\Delta B_{g,1980-2010}$ is the mean of the mass balance anomalies for 1980-2010, which is used to correct for the bias between $B_{geod-g,1980-2010}$ and the observed mean*

		glacier mass balance over the period 2011-2020. This way, the extrapolated cumulative annual mass balance for each glacier agrees with long-term observed mass change from remote sensing. *(L168-170)*
	More info needed for the optimization of the daily mass balance model	We added an explanation to the text that the daily mass balance model is calibrated each year to fit the various seasonal mass balance observations (point winter mass balance measurements and summer/annual ablation) (L170-172). *For step 4-6, in which we downscale the seasonal and annual glacier mass balances to the daily resolution, a distributed accumulation and temperature-index model was used (see e.g. Huss et al., 2015, 2021; GLAMOS, 2024). It is applied to each of the 28 glaciers with in-situ mass balance measurements. For each of these glaciers, accumulation and ablation are simulated using model parameters that are optimized to best match all available point-based winter and annual/summer mass balance measurements each year, as well as geodetic surveys of multi-annual mass change. The forcing of the model comes from nearby meteorological stations. The model computes daily mass balances on a fine spatial grid that are then aggregated to glacier-wide cumulative time series.*
	Explain the meaning of "L"	We clarified the compensation level "L" in the text: *L is a percentage indicating the extent to which the surplus glacier melt can compensate for deficits in precipitation, snowmelt (only in summer), or increased evapotranspiration. A value of 100% means that the surplus glacier meltwater could fully compensate for the deficits in the other water balance terms, resulting in near-normal streamflow (ΔQ=0). Values below 100% indicate only partial compensation, whereas values greater than 100% indicate overcompensation, i.e. the surplus meltwater exceeds the deficits.* (L235-240).
	Better explain the error term	We clarified in the methods part what the error term means and where it is added (L244-248): *Since it is not known which component causes the ϵ to deviate from zero, the term was once added to the surplus glacier melt component (ΔG, and once to the water deficit drivers (ΔP (+ΔS) – ΔET) in equation 4 to*

		calculate the uncertainty in L. Depending on the sign of ϵ, it can refer to an over/underestimation of (one of) the respective water balance anomalies or it could relate to water transfers from or to the catchment, affecting ΔQ in equation 5. Thus, in total, we derived three estimates of L per catchment, indicating the maximum range of possible values.
Results	Fig. s3 say that the numbers are for 2022	Thank you for pointing that out
	Add boxplots with abs and anomalies for the various water balance components	Figure 3 shows the absolute anomalies for all basins and corresponding catchment groups with a similar level of glacierization. To provide context to what these values mean, we added the absolute values of the various water balance components in the SI fig. 10. To make this more explicit, we added the following sentence: *The absolute values, instead of the anomalies, of the various water balance components in 2022 are shown in Fig. S10 (L304).* We opted for bars instead of boxplots, to immediately be able to compare the sizes and signs of the various water balance anomalies with one another and thus see which one is most important. In a boxplot version, this would be much more difficult to grasp.
	Add color coding to figure 4	We added the basin color coding to this Figure.
	Add boxplots for all variables for annual and summer and also for the error term, it would be a summary of Fig s6 (recommend to add to the main manuscript) and partly fig 4	Similar to the comment above, we do not see the added value of adding boxplots, because all information is already included in the manuscript, namely in Fig S10 (old figure S6). We choose to focus on the anomalies instead in the main manuscript. Adding both in the main text would make the manuscript too long and it would lose its focus on the anomaly compensation.
	long-term perspective would benefit from restructuring. Go more clearly row-wise or basin wise through fig 6. Also, mention the symbols you are referring to, it is not clear if the text is about the triangles or the circles or both. Some of the generalized statements might not be completely correct. It may help to make a subchapter for the detailed 2003-2022 comparison	Thank you for pointing out the need for clarification in this part. We improved the text throughout Section 5.1 by indicating what part of the figure we are referring to in each sentence, including which symbols. We also checked the statements and removed some of them, also to shorten the text: *Zooming in to the more recent extreme years (1998, 2003, 2018 and 2022), 2022 had the highest annual net volume loss (Ma). However, the total glacier melt volume in 2022 was smaller than in 2003, despite higher specific melt (Mt, Table 4, and Fig. 7 column 1, row 3). This shows that the ongoing glacier retreat (21% reduction in glacier area between 2003-2022) dominated the difference in meltwater*

		volume responses to the extreme years of 2003 and 2022, at the Swiss-wide scale and for the four large basins, which has important hydrological implications for summer water supply (Fig. 7 rows 2-3). At the scale of individual months, July 2022 still showed highest meltwater volumes, for all glaciers together, and for the Rhine and Rhone basins (Fig. 7, column 3, row 2-3). *In terms of streamflow, the annual minimum flow of 2022 had never been that low at the outlets of the four basins, but for the Rhone basin (Table 4, columns 7-10). Annual, June, July and August streamflow sums were lowest in 2022 (Po and Danube) or comparable to the extreme of 1921 (Rhine and Rhone) when comparing to the set of extreme years, (filled triangles for the basin outlet, filled circles for the average of the long-term stations, Fig. 7, rows 4-7).* *The pattern of streamflow variations across these extreme years resembles mostly the fluctuations in meltwater volumes, especially in the Rhine and Rhone basins, but precipitation deficits play an important role too. Around 1950, the construction of big reservoirs started. It is difficult to distinguish the effect of these reservoirs on streamflow during extreme years, as the earlier years (1921, 1928, and 1947) and later years (1998, 2003, 2018, 2022) were also characterized by very different amount of meltwater volumes. One catchment in the Rhine basin with long-term data can be classified as natural (square in Fig. 7, row 4), thus without reservoir influence. This catchment shows that streamflow follows fluctuations in meltwater volumes, but in 1947 (Annual and June) and 2022 (Annual, June, July and August), precipitation deficits were dominating. Relative glacier meltwater contributions to streamflow were among the highest in 2022, in particular when comparing the more recent extreme years (Figure 7, rows 4-7, open symbols). In the Rhone and Rhine basins, relative glacier meltwater contributions to streamflow were among the highest in July 2022, with around 20% for the Rhine at Basel, and close to 100% for the Rhone at Porte du Scex. These contributions strongly diminish at the annual scale (5%), but are still substantial for the Rhone basin (40%). The relatively constant or increasing relative contributions underscore how the absence of other*

		water sources enhances the importance of glaciers, highlighting their continued role during droughts even as overall meltwater volumes decline Furthermore, we created a subchapter for the 2003-2022 comparison, as well as for the sensitivity part.
	July 2022 – 2018 not clear	This has removed in the revised version.
	Meaning of rx in table 3	Yes, indeed, this indicates which rank this 7-day lowest flow of 2022 had in the full observed timeseries. This has been added to the caption.
	Figure 7 should be summarized in a boxplot? Or a table that summarizes the counting of the catchments	As indicated by the reviewer before, maps can be helpful to understand spatial patterns. Summarizing Fig. 7 (old manuscript) in a boxplot would mean losing the spatial information. In the revised text, we improved the description of the number of catchments and corresponding percentages, to avoid having another table: *In July 2022, positive degree-day sums and the specific glacier mass balance were higher/more negative than in 2003 for almost all catchments ("T" and "B" in Fig. 8, in 75of the 76 considered basins). However, only in most of the Rhone basin and parts of the Rhine basin (the western part, Aare sub-basin), this led to higher glacier meltwater volumes (48/76 catchments) ("G" in Fig. 8). Even though meltwater volumes were higher here, not everywhere this led to higher streamflow volumes ("Q" in Fig. 8). Only in 16/76 catchments streamflow was higher in July 2022 than in 2003. Only in 13 of the 76 catchments both streamflow and meltwater volume was higher in July 2022 than in 2003. Thus only in 30\% of the catchments more meltwater resulted in higher streamflow amounts (13 of the 48 with higher meltwater volumes). In all the other catchments (35 of the 48 catchments), the higher meltwater volumes could likely not compensate for the higher precipitation deficits and less snowmelt ("S") in 2022 compared to 2003, resulting in less streamflow. Alternatively, for catchments downstream of reservoirs, more water may have been stored in the reservoirs in 2022 than in 2003, for which no data is available.* *Over the summer period (MJJA), only 20/76 catchments showed higher glacier meltwater volumes in 2022 than in 2003, despite more negative glacier mass balances for most of the catchments (62/76) (Fig. S13). This translates*

		to 68% (42/62) of the catchments showing a declining meltwater supply in summer, despite higher melt rates. In the remaining catchments (located in the eastern part of Switzerland, 14/76), 2003 was more extreme in terms of glacier melt conditions than 2022. Streamflow was lower in summer 2022 than in summer 2003 almost everywhere, despite higher precipitation in 2022 for around half of the catchments. This highlights the complex interaction of glaciermelt (less in 2022 in majority of catchments), snowmelt (less in all catchments), rainfall (less in half of the catchments) and evapotranspiration (more in approx. 1/3 of the catchments) that all contribute to runoff generation, but in varying proportions from up- to downstream. The combination of higher glacier meltwater volumes for part of the catchments and lower streamflow in 2022 compared to 2003 led to overall higher relative glacier melt contributions to streamflow (Fig. 6c).
	Is there any chance to evaluate reservoir storage effects?	This is very difficult. Even if we were to know the amount of storage that is available in reservoirs (total storage), we have no information about how much water was actually stored in 2022, and for example 2003. This means that we do not know if more or less water was stored in 2022 than in 2003. For this one would need up and downstream info of reservoirs and such a set-up we don't have at the scale of Switzerland. We added this to the discussion on the unknown effects regulation measures:. *Last, the measured streamflow data is a source of uncertainty too. Although the relatively dense network of gauges with long-term observations in a mountain setting is rather unique, many of the observations are influenced by water transfers or lake regulations. Without knowing the details of such regulations, and how they vary during extreme years, these influences on the analyses can only implicitly be taken into account, for example by providing a range of compensation levels in Fig. 5 that include the possibility of water being im- or exported to/from the catchment*
	Statement about fig. 5 Might be valuable to notice here then that this is true especially for glaciations ~ >10% (this seems the point of divergence between purple and orange)? Also, it reads as if	Thank you for pointing this out. The 10% visibility threshold also relates to generally small contributions at low glacierizations, so that differences are more difficult to see. We

	the authors point to Fig 5b, if so, maybe focusing on the summer period (5c) might underline the statement even more?	therefore did not add this point. We changed referring to Fig. 5C instead of Fig. 5b.
	Fig 7 positive degree day - with respect to threshold of 0 °C or varying with respect to a calibrated melt temperature threshold within the optimzation procedure?	Yes this value is based on 0 degree and catchment average temperature, it is unrelated to any modelled DDF. We therefore kept this unchanged.
	Check sentences 375 and 376 for redundancy and vagueness because of "overall" and for "specific basins"	Thank you for pointing this out. We changed into: *At the Swiss-wide scale, for the four large basins, and at the individual catchment level, results indicate a decline in total glacier meltwater supply, but with exceptions regionally and locally, and for the particularly extreme month of July 2022.*
	The sensitivity part is a little undervalued. Needs its own sub-section?	Yes, we isolated this text and created an own sub-section to present and discuss the changing sensitivity section 5.5.1 in the new version).
	If I understood correctly glacierization characterization is based on the year 2016, do the authors expect this choice to affect the results?	Yes, the glacierization is based on the 2016 inventory. We understand the phrasing causes some confusion, as these glaciers, for example, may not have been in the 0.1 km2 group back in 2003. Nevertheless, for reasons of consistency, the same group of glaciers - classified according to the 2016 glacierization - is required.
	It would be interesting to see how the behavior looks as function of elevation (likely similar). At least it might be interesting to add to the Supplementary Fig. S6 a row for temperature anomalies by elevation.	Elevation would be more tricky, as it is not only the median elevation of the glacier, but also the elevation range that matters. We have added the sensitivity figure against elevation (instead of glacier area) to the SI (Fig. S13)
	Keep everywhere the distinction between net and total meltwater volumes	We have applied this throughout the revised manuscript.
	But to be fair the Rhone seems to be driving also the overall Swiss pattern where I would evaluate the change after 1980 not very significant or in other words relatively stable (especially given the same level of volumes before the local high in the 80s/90s).	Indeed, since the majority of the Swiss glacier volume is located in the Rhone basin, the Rhone basin also drives the overall Swiss pattern.
	What is missing in the description of Fig. 9 currently is the interannual variability which from visual inspection seems to be much higher in the first half of the time series?	Larger glaciers respond indeed more strongly in terms of volume, and could therefore affect the interannual variability. Furthermore, this may also be driven by the scarcer annual mass balance data before ca. 1960: having less data points to extract year-to-year variability from could result in higher variability. Since the manuscript is already rather long, we decided to not further extend the focus and include an analysis on the interannual variability. Nevertheless, we added a short

		interpretation of this observation to the Discussion section.
	L410 – a change in the overall writing quality	Thank you for pointing this out. We have put particular focus on the re-writing of this part. See track-changed manuscript for the actual changes.
	The drought terminology might be revised by the authors as extreme years (wrt temperature and precipitation) do not necessarily provide a comprehensive or differentiated drought picture.	Indeed, extreme temperatures and low precipitation do not necessarily mean drought and a heatwave. In this study we take a comprehensive approach and look at all variables important to characterize meteorological and associated hydrological drought. Since 2022 is well established as a drought over central Europe in recent literature (Tripathy & Mishra, 2023; Avanzi et al., 2024; Schumacher et al., 2024) we do not think that classification according to a standardized index or threshold is required. Accordingly, we don't think there is a need to revise the drought terminology.
	"*However, a changing Θ may not only relate to decreases in glacier area reducing meltwater volumes, but also <u>to changes in glacier surface albedo</u>, due to changing snow cover duration or the deposition and accumulation of dust at the surface (e.g. Gabbi et al., 2015).*" ▯ and thus to local temperature variations	We prefer to stay with the albedo explanation and the effect it has on the radiation terms and the energy available for melt. Local temperature variations would indeed be relevant, but are not captured in our temperature data.
Discussion – 6.2	*In this study, 52 catchments showed a possible precipitation under-catch, which could be corrected with a multiplication factor for only 7 catchments. For the other influenced catchments, any applied correction to close the water balance may rather "correct" the human influence affects instead of the precipitation.* This is rather confusing, where do these numbers now come from and what is exactly meant with correct the human influence, please be more precise.	We removed these numbers, as they were already mentioned in the Methods section. We also clarified what we mean with "correcting" the human influence, *Here we applied a correction factor for 7 catchments, that we classified as natural, only to close the water balance for catchments with deviations more than 25% (Section 3). For the other catchments, with a degree of human influence, such a correction cannot be applied as we cannot distinguish if the non-closure of the water balance comes from a precipitation underestimation or from human influences for which we do not know their magnitudes. Without more insights on the degree of human influence, we thus lose information by having to exclude catchments in some of the analyses*
	I think it would be good to provide ET (or for all vairable) maps in the appendix to get an idea on the absolute numbers across the different catchments.	We agree and therefore did already provide the absolute numbers of ET and all other variables in the supplementary information Figure S10, plotted against elevation and color coded according to main basin. We refer to this figure now at the location of this comment (Section 6.2)
	The non-closing water balance issues could also arise from the glacier storage change estimations. Although the extrapolation procedure was	Since we do not know which term causes the non-closure of the water balance in each of the 88 catchments, or if it is even caused by

	carefully designed and improved in comparison to previous estimates (Huss, 2012; Cremona et al., 2023), the large variability in glacier geometries, the terrain surrounding glaciers, and local conditions make the extrapolation of measurements on only a few glaciers to 1400 glaciers a challenging task. I fully agree to that and thus think that more attention should at least be given to the error term of the water balance closure/computation. Also, I think it would be beneficial to stronger support the choices of the interpolation at least by providing more references.	processes not accounted for (human influences), we rely on acknowledging the error term and discussing its potential causes. The glacier mass balance interpolation method may be one source, but is certainly not the only one. We identify all of the potential sources in the discussion. For the glacier mass balance interpolation method we added references to Dussailant et al. (2025) and Ohmura et al. (1992).
	I would definitely recommend providing some maps/infos on which basins are affected.	We added a map in the SI showing the basins that are affected and which ones can be assumed to be “natural” (SI Fig. S2).
Discussion – 6.3	total meltwater, right (Table 3)?	Indeed, we referred to total meltwater.
	How future extreme years may evolve thus depends on the extremeness of future conditions and the timing, determining the interval for glacier area changes. Not sure if I get this sentence right, do the authors just want to say "the status of glacier retreat"?	Yes, thank you. We changed into “status of glacier retreat”
Conclusions	While the conclusion reads generally well, it might be improved by adding a little bit more remarks/statements on the hydro-meteorological conditions the year faced and provide thus the boundary condition for what we have seen.	Thank you for pointing out the need to add more statements on the hydro-meteorological conditions in the conclusion, this was added in the revised version at the start of the conclusions. *This study analyzed the role of glaciers during the drought year 2022 in Switzerland, which was characterized by a very dry winter, and particularly dry months in May and July, combined with high summer temperatures, especially from May to July*
	Do these numbers come from Fig. 3?	They come from Fig. 4 (old)
	Maybe vice versa add how many catchments in 2022 showed higher melt rates than in 2003	Yes, this has been added.

New Figures and Tables:

Table 2. Overview of the datasets used in the study. (O) and (M) in the "Data" column refers to Observations, or Modelled, respectively. P stands for precipitation, T for temperature, SWE for Snow Water Equivalent. the "n" column indicates the number of catchments/glaciers for which data was available in this study.

Data	n	Variables	Period	Temp. res.	Spat. res.	Source
Streamflow (O)	88	Q	varying, 1900-2022	daily	catchments	FOEN, Cantonal stations, hydropower companies
Meteorology grid (O)	-	P, T	1961-2022	daily	~1 km x 1 km	RhiresD and TabsD (MeteoSwiss, 2019, 2021)
Meteorology station (O)	44 P & 16 T	P, T	1900-2022	daily	-	MeteoSwiss
Evapotranspiration (M)	-	ET_a	1981-2022	daily	500m /1 km	PREVAH model Viviroli et al. (2009); Höge et al. (2023)
SWE (O/M)	-	S	1999-2022	daily	1 km	SLF Swiss operational snow product
In-situ mass balance (O)	28	B, B_w, B_s	varying, 1915-2022	annual, seasonal	glacier	GLAMOS (2024)
Geodetic mass balance (O)	1400	B_{geod}	1981-2010	multi-annual	glacier	Fischer et al. (2015)
Glacier outlines (O)	1400	A_{gl}	1973, 2016	-	glacier	Linsbauer et al. (2021); Müller et al. (1976); Maisch (2000); Paul (2003)
Glacier volume (O)	1400	V_{gl}	2016	-	glacier	Grab et al. (2021)
Glacier storage change (O/M)	1400	G	1916-2022	daily	-	This study

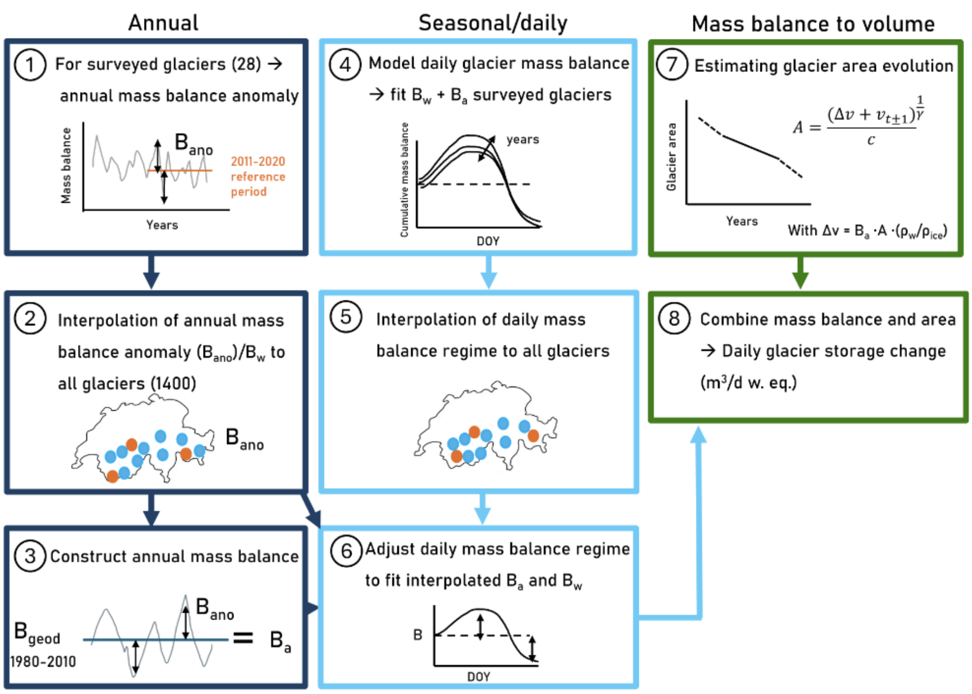

Figure R1.1 Conceptual flowchart of the glacier mass balance extrapolation procedure

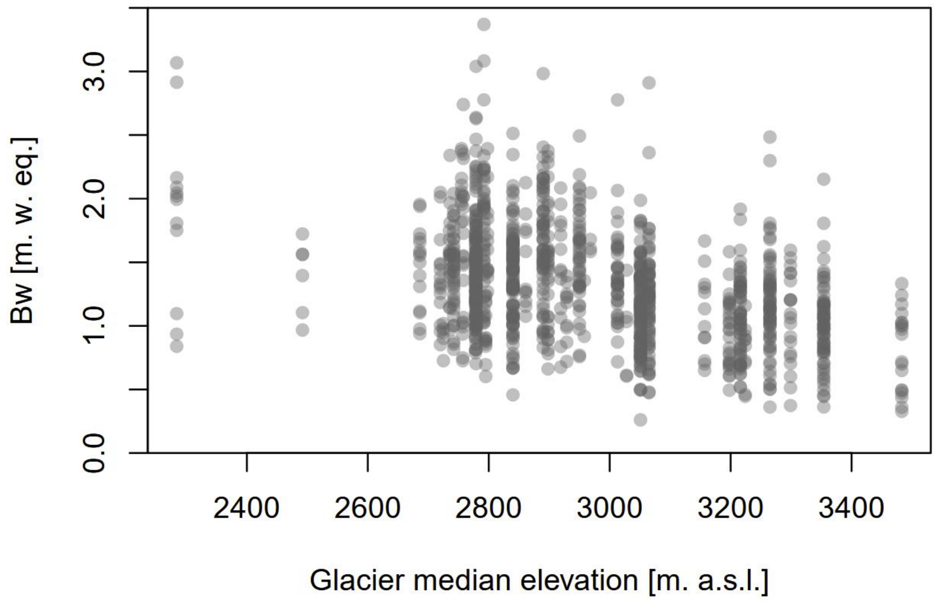

Figure R1.2 Observed annual winter mass balances plotted against glacier median elevation. Points represent all available data between 1915 and 2022.

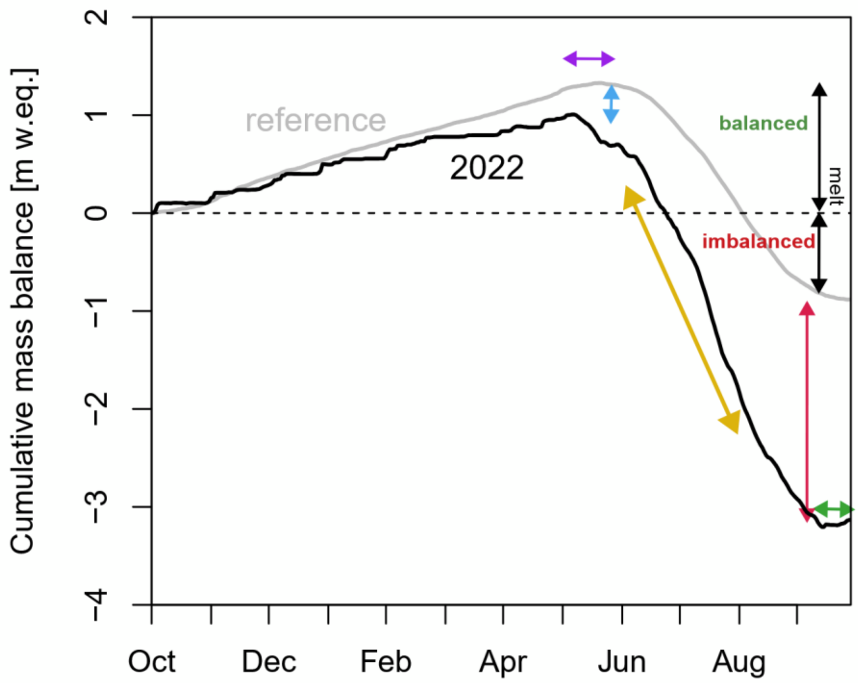

Figure R1.3 Schematic of the glacier mass balance attribution, with the colors referring to the boxplots in Fig. 3 of the main text. The lines refer to the reference (1991-2020) and 2022 cumulative mass balance time series. The blue and red arrows indicate the anomalies in winter and summer anomalies, respectively (Fig. 3a), the purple, green and yellow arrows to the anomaly in starting, end and intensity of the melt season (Fig 3b) and the black arrows indicate the part of melt that is balanced and imbalanced (Fig 3c).

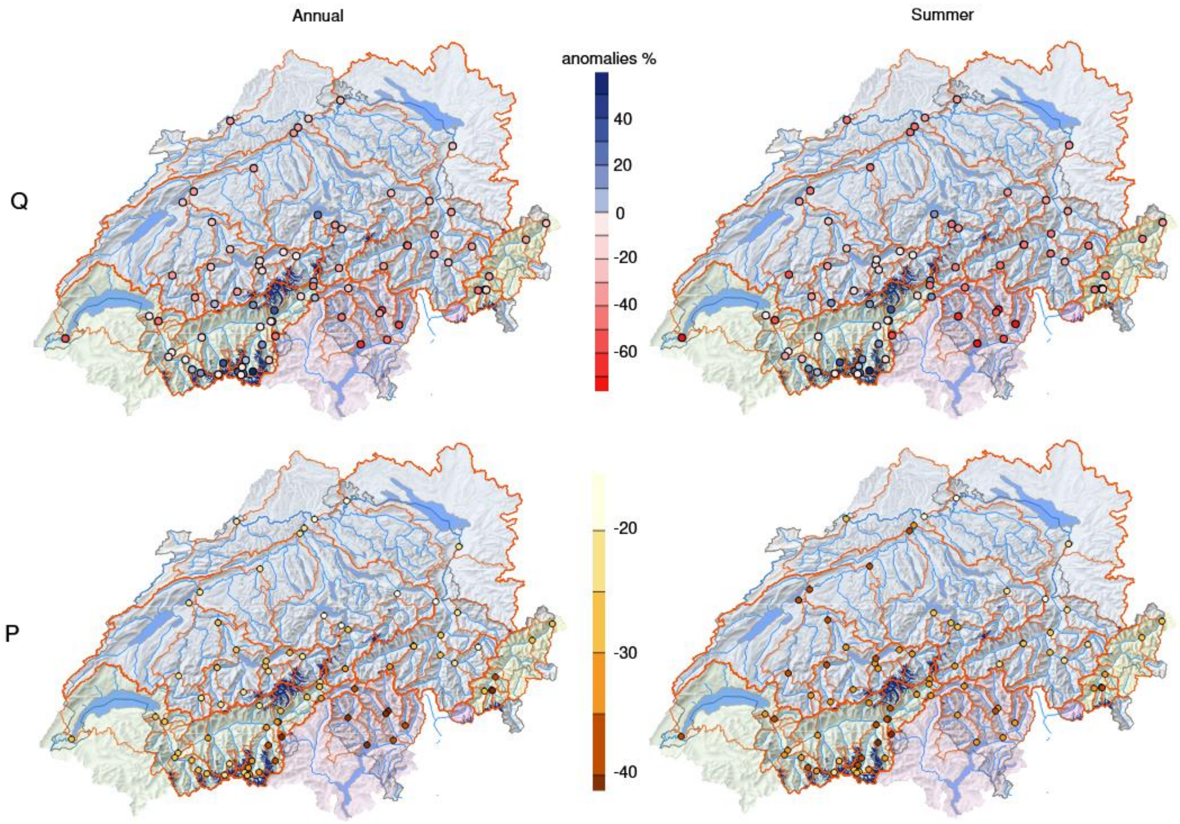

Figure R1.4 Relative anomalies of streamflow (top row) and precipitation (bottom row) in 2022 compared to the reference period 1991-2020, for annual (left column) and summer (right column) timescale for all catchments (dots).

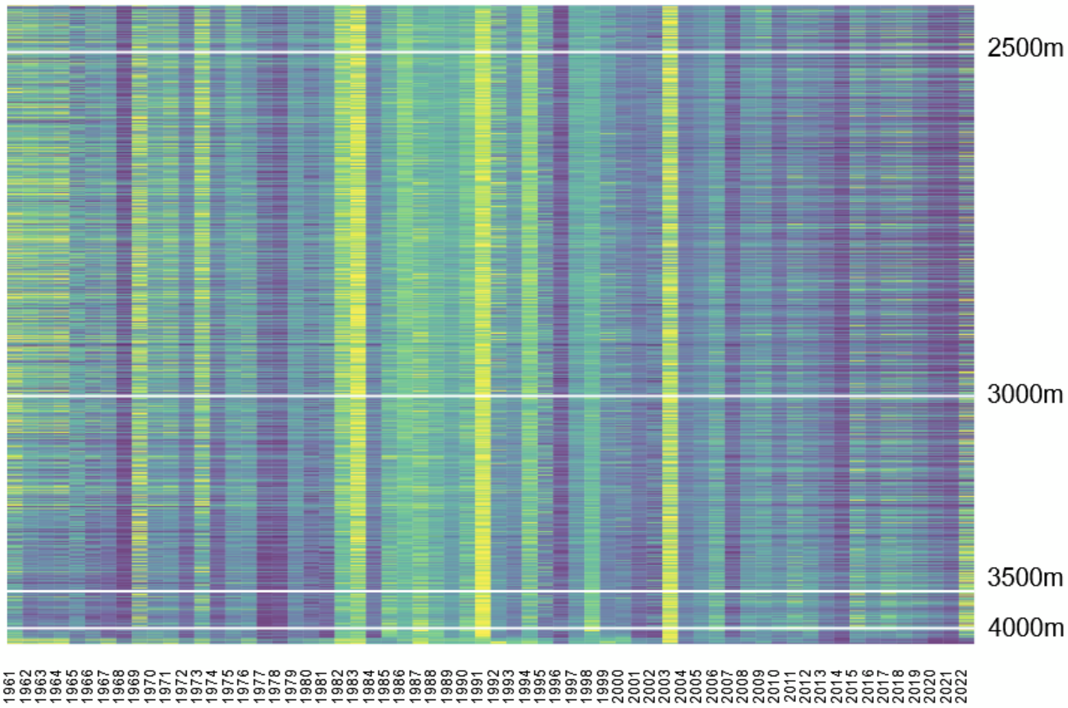

Figure R1.5 Similar as Fig. 9 in the main text. Glacier melt sensitivity θ for each of the 1400 glaciers (rows), from 1961 to 2022 (columns). Here, the glaciers are sorted by elevation instead of glacier size, as in Fig. 9. Yellow indicates high sensitivity, whereas blue indicates low sensitivity.

References:

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Schumacher, D. L., Zachariah, M., Otto, F., Barnes, C., Philip, S., Kew, S., ... & Seneviratne, S. I. (2024). Detecting the human fingerprint in the summer 2022 western–central European soil drought. *Earth System Dynamics*, *15*(1), 131-154.

Avanzi, F., Munerol, F., Milelli, M., Gabellani, S., Massari, C., Girotto, M., ... & Ferraris, L. (2024). Winter snow deficit was a harbinger of summer 2022 socio-hydrologic drought in the Po Basin, Italy. *Communications Earth & Environment*, *5*(1), 64.

	Reviewer	**Author reply**
General	The author investigated the driving factors for streamflow changes during the 2022 drought in Switzerland. I enjoyed reading this paper. Glacier melting has accelerated in recent years, raising a key question: Will peak runoff arrive by the middle of this century? The author illustrated that enhanced glacier melt may not compensate for reduced glacier area, potentially leading to decreased glacier runoff in the future. The paper is well-written and well-structured, except for the results section, which could be more conclusive. My major concerns relate to data quality control. It would be valuable to include one or several basins with robust in situ observations to support the study's conclusions. I recommend minor revisions before considering publication.	We thank the reviewer for carefully assessing our manuscript. We are happy to read that the reviewer enjoyed reading the manuscript. We have substantially revised the Results section, so that key findings are better highlighted and explained. See tracked-changed manuscript for all changes applied to the text. We agree that data quality control is important for supporting the conclusions and are addressing this in the manuscript by calculating the closure of the water balance. We would like to stress that the basis of this study is indeed to use in-situ observations wherever possible. This means that all streamflow data is in-situ data, which is combined with interpolated or modelled data of glacier storage change, precipitation, SWE and evapotranspiration. No basin exists that would have in-situ observations for all water balance terms. For example, even in catchments where glacier mass balance is measured, this only represents the mass balance for that one specific glacier, whereas a catchment typically includes a handful to a lot more glaciers. Precipitation and SWE are observed locally, but that does not provide information about the catchment-wide patterns. Evapotranspiration observations are even more scarce. In summary, all robust in-situ data that are available are already included in the study. Since many of the analyses refer to consistent regional patterns, we think highlighting one or several specific basins won't add different insights. In the revised manuscript we stressed that the study uses all available in-situ data available at the large regional scale (L86-90): *For the glacio-hydrological characterization of 2022 and the comparison with past extremes, we assembled all available regional-scale observations and complemented this with model-based estimates at a daily resolution (Table 2) to derive the water balance terms for all of the catchments.* Thank you for the detailed comments. We address them here below.
Abstract	R2.1 - Line 15: "with the difference in summer/July reflecting the extremeness of the melt conditions." This is not entirely clear to me. Could you clarify what "extremeness" refers to in this context?	With "extremeness" we refer to the anomalous meteorological conditions, which were particularly extreme in July, and a bit less extreme when looking at the whole summer of 2022. The more extreme (deviation from normal conditions), the more the glacier would melt, and thus be more able to offset the reduction in glacier area. Since

		this would use quite some space to explain, we decided to simplify the sentence: *In 2022 versus 2003—the most comparable recent extreme summer—total glacier meltwater supply decreased in two thirds of the catchments over the entire summer, and in one third in July. In the remaining catchments, the more intense specific melt of 2022 could offset the 21% glacier area loss since 2003.*
Methodology	R2.2 - Line 100: Can you explain why 25% was chosen as the threshold? "If the ratio exceeded 1 and the catchment was classified as 100% natural, we applied a uniform multiplication correction to the daily precipitation data." The bias in observed precipitation depends on gauge type and varies across seasons. If the bias primarily stems from winter under-catch, glacier accumulation could be significantly underestimated. The author briefly addressed this in Section 5.3 and the discussion. It would be interesting to include more analysis based on in-situ observations, such as comparing winter glacier mass balance (GMB) with observed winter precipitation to check if biases are consistent across years. In general, the data quality control section needs more explanation, as it directly impacts the results. A schematic illustrating this process would clarify the section.	25% was chosen, weighing off the effects of a too strict threshold resulting in few catchments remaining in the analyses, and a too high threshold including catchments that have a clear deficiency in the data that would hinder interpretation of patterns that we are after in this study. This was added at L100: *A threshold of 25% was chosen here, weighing off the effects of a too strict threshold resulting in few catchments remaining in the analyses, and a too high threshold including catchments that have a clear deficiency in the data that would hinder interpretation of patterns that we are after in this study.* It is correct that glacier winter balances could be used to test the biases in winter precipitation. But at the same time, these are very localized comparisons where also wind redistribution and avalanches play a role, and cannot be scaled to, for example, catchments as big as half of Switzerland. Moreover, we would like to emphasize that these precipitation values are only used to analyze precipitation deficits to describe the water balance and its anomalies. The precipitation data are not used as direct forcing for a model, and so the bias in precipitation does not propagate to the streamflow observations or the interpolated glacier mass balances. Indeed, the uniform multiplication factor correction of precipitation is a widely used method in hydrological studies, but misses seasonal/annual variations in the bias. In an ideal case, precipitation is corrected seasonally, annually varying and perhaps also sub-spatially (within the catchments) but information to derive such spatially and temporally varying bias corrections at the scale of Switzerland is missing. By the dedicated paragraph in the discussion on data uncertainty we have already highlighted potential problems, including the uncertainty of precipitation at high elevations. A more thorough data quality control would perhaps include more

		measurements, but that would be outside of the scope of this country-scale study.
	R2.3 - Section 4.1: I like this method, but it could be described more clearly. Consider moving Figure S2 to the main text and incorporating the method or data preprocessing workflow into that figure.	We have added a flowchart figure about the extrapolation of the glacier mass balance data to the manuscript (new Figure 2) (See Figure R1.1 in the response to reviewer 1)
	R2.4 - Line 190: γ = 1.8. Does this value apply to all glaciers in the study region? This seems slightly high for glaciers in Switzerland.	Indeed, we used one value for all glaciers in Switzerland. This higher value for gamma resulted from the log-log plot of area and volume for Swiss glaciers in 2016 and 2022. This explanation was added to the manuscript (L190): *where c is a glacier-specific constant, and* γ*=1.8 is an exponent which was adjusted to fit the observed area and volume changes between 2016 and 2022*
Results	R2.5 - Figure 2b: For contributions of the late ending of the melt season to ΔBs, why are the bottom whiskers invisible in the Rhine, Rhone, and Po basins compared to the Danube basin? This is particularly notable since the Po and Danube basins are geologically similar.	The bottom whiskers are invisible as the 5%, 25% and 50% percentiles of the late melt contributions of the set of glaciers for those basins were 0. In these basins, many glaciers did not have a later end of the melt season than during the reference period.
	R2.6 - Figure 3: It would be interesting to include a figure with units in percentage, as the absolute values of these terms differ.	Yes, we included the figure with relative anomalies in the SI (Fig. S9) and added the figure here below. The absolute values indeed differ, but we choose to display these in the main manuscript as the absolute anomalies explain and quantify the compensation effect, which is not the case for the relative ones.
	R2.7 - Line 320: "The relation between glacier melt contribution to streamflow and level of glacierization is exponential, showing a steep increase in melt contributions for catchments with 0–20% glacierization, which diminishes for catchments with more than 20% glacierization." This is interesting, but do you have an explanation for this pattern? Be cautious with this conclusion, as I don't see this trend in the reference period.	Indeed, this relationship is less clear in the reference period, but also there an exponential behavior could be identified, which is most clear if we look at the summer melt period. A possible explanation could be because most catchments which are highly glacierized are located in the drier Rhone basin so that a different relationship between glacier melt, precipitation and evapotranspiration may exist here. Or it may relate to the decrease in evapotranspiration with increasing glacierization, offsetting the decrease in precipitation at very high elevations. This explanation was added to the results, L339-340: *The reason for the exponential relationship between catchment glacierization and relative glacier melt, especially during dry years, is not completely clear. It may relate to changing climatological gradients with elevations or to the cluster of highly glacierized catchments that are all located in the drier Rhone basin.*
	R2.8 - Figure 4: The comparison of uncertainty ranges between different groups is unclear and seems unfair. Due to the logarithmic scale, the	The uncertainty range is calculated the same way for all catchments. Indeed, due to the logarithmic scale, the length of the uncertainty range does not

	uncertainty for highly glaciated basins appears much smaller than for others.	scale with the uncertainty, i.e. it looks much smaller for the highly glacierized catchments. Without a logarithmic scale we would lose important information on the lower glacierized catchments. We added a note in the caption that this distorts the impression of the uncertainty ranges and added a non-logarithmic version in the SI (Fig. S12). revised text: *Note, that x- and y-axis are logarithmic, distorting the scale of the uncertainty ranges (in the SI Fig. S12 shows the plot without logarithmic y-axis).*
	R2.9 - Line 365: Do you have any data to support this aspect?	We assume the reviewer refers to this statement *"Only in 16/76 catchments streamflow was higher in July 2022 than in 2003, and for three of those (two in Po basin and one in Rhine basin) this did not relate to higher glacier meltwater volumes. Thus only in 30% of the catchments more meltwater resulted in higher streamflow amounts (13/48)".* The higher streamflow in 16 minus 3 catchments in July 2022 is hypothesized to relate to higher meltwater volumes, as described in the text. For the three catchments that did not show higher meltwater volumes, but did show higher streamflow volumes in 2022 as compared to 2003, there are three possible explanations: 1) it could relate to more water being released from storage (artificial or natural – e.g. wetter conditions previous month), 2) or a dominant role of ET (which was less in the Po basins in July 2022 compared to July 2003 - Fig. 7) or 3), alternatively, it relates to uncertainties such as a potential underestimation of the glacier area, so that actually more meltwater was generated than currently estimated. To focus on the glacier meltwater related patterns, these causes were discussed more generally in the discussion.
	R2.10 - Line 375: Could you add a definition of "changing sensitivity"? Consider moving the sentence from Line 420 to this section.	Yes, we have added, "here expressed as meltwater volume per unit of temperature"
	R2. 11- Figure 8, Panel B: Why do glacier area changes appear almost linear after the 1970s? How was the initialization of the glacier state handled in the modeling?	Indeed, we decided to perform a linear interpolation of glacier area in between the two available inventories in 1973 and 2016. We consider this the best estimate of glacier area in between these two fixed glacier areas for every glacier. Volume-area scaling was only applied for updating glacier areas after 2016, and before 1973, respectively. This procedure is explained in the Methods section 4.1 (L185-195): *Between 1973 and 2016, glacier areas for each glacier were linearly interpolated between the two*

		respective inventories (Müller et al., 1976; Linsbauer et al., 2021). Before 1973 and after 2016, the area A of a glacier was computed based on its annually updated volume V by using volume-area scaling (Bahr et al., 1997): *where c is a glacier-specific constant, and γ=1.8 is an exponent which was adjusted to fit the observed area changes, showing that smaller glaciers lose their area much quicker than larger glaciers. c was derived for each glacier individually based on the known values for A and V for the 2016 inventory (Grab et al., 2021). For estimating glacier area during years outside the 1973-2016 window, Equation 3 was applied by computing an updated glacier volume (V ± ΔV) based on the extrapolated* *mass balance and glacier area of previous or next time step (depending on whether the equation is used for determining an area after 2016 or before 1973) and a volume-to-mass change conversion factor of 850 kg* m^{-3} *(Huss, 2013).* Based on this approach, there is no need for an initialization of the glacier state. Extrapolated ice volume changes in every year allow updating the area also before 1973 based on the scaling law.
	R2.12 - Section 6.2: As mentioned earlier, providing more in-situ data in the supporting information would be beneficial. This method could also be applied to other mountain regions globally.	We do not entirely understand the reviewer's request here: We cannot print all in-situ data used in this study in the SI. The data description provides sources and references for all data that are used which should allow full reproducibility of the applied approaches.
	R2.13 - Line 450: Out of curiosity, what method was used to measure discharge in Switzerland?	The discharge data from almost 90 catchments was obtained in most cases from the Swiss federal hydrometric gauging station network, combined with stations from cantonal and private networks. Discharge at these stations is measured in a variety of ways, depending on the setting, using pressure sensors, velocity-area (radar) and weirs. The data from the authorities is provided as discharge data only, i.e. not the raw data. The data description was extended to include this information.

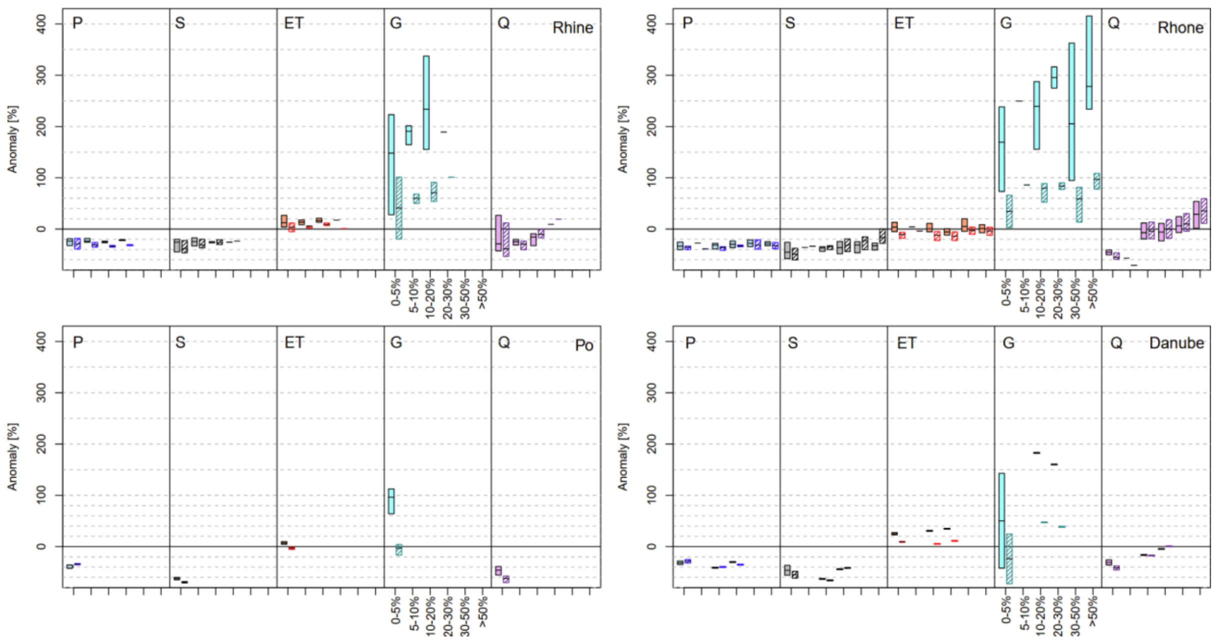

Figure R2.1 Water balance anomalies for the four basins, with grouping of catchments according to glacierization, similar to Figure 4 in the main text, but here the boxes indicate the relative anomalies, instead of the absolute ones that are presented in the main text. The top and bottom of the bars refer to the min and max of each glacierization class, while the black horizontal line in the middle refers to the average. The filled bars show annual anomalies, while the dashed bar shows summer anomalies.