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Swiss glacier mass loss during the 2022 drought: persistent streamflow contributions amid declining melt water volumes

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Abstract. The year 2022 was extremely warm and dry in Europe, resulting in a severe hydrological drought. In Switzerland, part of Europe's water tower, streamflow in glacier-fed rivers could have been even more reduced if the situation had not led simultaneously to extreme glacier melt. Here we analyze the role of glaciers during the 2022 drought for 88 glacierized catchments by combining streamflow and meteorological observations with estimations of snow water equivalent, actual evapotranspiration and daily glacier storage changes. We also compared the year 2022 to earlier exceptionally warm and dry years (1921, 1928, 1947, 1998, 2003 and 2018) to assess if the ongoing glacier retreat has already caused a declining meltwater supply in such extreme conditions. Results show that 60-80% of the total glacier melt in 2022 came from net mass loss (imbalanced melt). During summer, the increased melt could completely offset the precipitation and snowmelt deficits for catchments with around 15% glacierization. Further downstream, the extra melt in summer alleviated water input deficits by up to 5% at Basel (Rhine) and 70% at Porte du Scex (Rhone). However, compared to other extreme years in the past, total melt volume has been noticeably declining due to a strong reduction in glacier area – despite more extreme melt rates per unit glacier area. In contrast, the relative contribution of glacier melt to streamflow stayed constant or even increased for some months, suggesting that glacier melt remains important during droughts. Comparing 2022 to 2003-the most comparable recent extreme summer- shows a declining glacier 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. This declining meltwater supply raises concerns for future drought situations.

1 Introduction

The year 2022 was characterized by extreme weather events, such as floods, droughts and heatwaves, all around the world. At a global level, the year was the fifth warmest year on record since 1880 (WMO, 2023). Throughout Europe, the summer of 2022 was the hottest since 1950 (Copernicus, 2023). Although the following years, 2023 and 2024, broke some of the temperature records, 2022 is still characterized as most recent extreme year in (central) Europe in terms of summer temperature in combination with a precipitation deficit. During 2022, a persistent high-pressure anomaly, centered over France, caused a

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spatially varying intensity in lack of precipitation, a series of heatwaves occurring from May until August, and drying out soils over Europe (Faranda et al., 2023; Tripathy and Mishra, 2023). The compound drought and heatwave hit particularly hard in Northern Italy, for which Tripathy and Mishra (2023) found a return period of 354 years. In combination with a large snow deficit building up during the preceding winter (Avanzi et al., 2024), the Po river in Italy experienced its worst streamflow drought of the past two centuries (Montanari et al., 2023). At the same time, the extremely warm summer of 2022, in combination with low snowfall in winter and several Saharan dust events darkening the snow, led to record-breaking glacier volume losses in the European Alps (Réveillet et al., 2022; Cremona et al., 2023; Voordendag et al., 2023).

Meteorological droughts, such as in 2022, propagate through the hydrological cycle to become a hydrological drought, with considerably less discharge in streams and rivers and low lake and groundwater levels (Van Loon, 2015; Van Lanen et al., 2016). In Switzerland, the drought of 2022 resulted in problems with water supply, restrictions on water use for households and agriculture, reduction in energy production from hydropower plants, restriction of navigation on the river Rhine and some lakes due to low water levels, and fish mortality due to high water temperatures (BAFU, 2023). During drought conditions, catchment storage elements are important to buffer and alleviate the propagation of meteorological droughts to hydrological droughts (Van Lanen et al., 2013; Van Loon and Laaha, 2015; Bruno et al., 2022). In the case of the extreme year 2022, in which snow melted away early in the year and groundwater levels were affected due to the prolonged duration of the drought, the relevance of glaciers as a catchment storage increased, providing this buffering role during summer (Pritchard, 2019; van Tiel et al., 2020; Ultee et al., 2022; McCarthy et al., 2022a). Even more so, glacier melt has the capacity to counterbalance some of the precipitation-driven water deficits during heatwaves by melting more glacial ice than normally (Van Tiel et al., 2021). The combination of above-average glacier melt and lower streamflow contributions from other sources (rain and snow) increases the relative contribution of glaciers to streamflow during concurrent drought and heatwaves. This makes glaciers, despite their relatively small size at the basin-scale, important for mitigating droughts, even far downstream (Huss, 2011; Koboltschnig and Schöner, 2011; Jost et al., 2012; van Tiel et al., 2023).

While the extra glacier melt during drought and concurrent heatwaves alleviates streamflow drought, the situation is very unfavorable from the glacier perspective. During such strong mass loss years, glaciers loose a significant part of their volume of which they do not recover from during times of unprecedented climatic warming (Vincent et al., 2017; Hugonnet et al., 2021). With ongoing climate change, there is a tendency of extremely hot and dry years to occur more often and to become more intense (Alizadeh et al., 2020; Mishra et al., 2020; De Luca and Donat, 2023). Vargo et al. (2020) showed that due to anthropogenic climate change extreme annual glacier mass losses are six to ten times more likely to occur for glaciers in New Zealand. How glaciers respond to extreme meteorological conditions depends on several factors: 1) the intensity of (lack of) accumulation and melt conditions, 2) their balanced state with the climate, and 3) their areal extent, which determines the volume of melt that can be generated. All of these factors are changing over time, and need to be considered to assess how retreating glaciers affect the buffering capacity of glacier melt during droughts.

In terms of glacier retreat and water resources, often the concept of "peak water" is analyzed, which describes how glacier meltwater volumes first increase due to a continuing rise in temperatures, but decline thereafter (the peak) when the volume and area of glaciers has diminished and the increased specific mass losses cannot offset the smaller glacier area anymore (Ragettli et al., 2016; Frans et al., 2018; Huss and Hock, 2018; Chesnokova et al., 2020; Rets et al., 2020; Wang et al., 2023). This trajectory often refers to smoothed time series of glacier runoff (Huss and Hock, 2018; Carnahan et al., 2019; Rounce et al., 2020), and therefore provides only information on the general trend but not on the changing glacier meltwater volumes during specific extreme years. Theoretically, glacier responses during extreme years could be different from long-term mean changes in glacier runoff, i.e. on average glacier melt volumes could be declining, while during an extreme year a new record of released glacier melt volume could be broken. For understanding the changing compensational role of glaciers, it is therefore imperative to focus on extreme melt years specifically and analyze how glacier melt water supplies have been changing in such years.

In this study, we examine the hydrological drought situation and the extreme glacier melt year of 2022. We bring together glaciological and hydrological observations and model-based estimates of all water balance terms and aim to attribute the causes of the extreme glacier melt and the downstream flow deficits to their hydro-meteorological drivers. We quantify how much glacier meltwater could compensate for the lack of rain and snowmelt in the summer 2022 and how this varies spatially and with distance from the glaciers. To examine if the balance between increasing melt rates and ongoing glacier retreat is turning into declining glacier meltwater volumes, we put the year 2022 into a long-term perspective and compare it with other extreme years in the past.

2 Study area

We consider all gauged glacierized catchments in Switzerland for which reliable data could be obtained through the federal network, the cantonal stations and private companies (Figure 1). In total, 88 catchments are included, with sizes varying from 9 km^2 to 35'877 km^2 (Table S1). These catchments contain 97% of the 1400 Swiss glaciers (Linsbauer et al., 2021) and are sub-catchments of the four main river basins Rhine, Rhone, Po and Danube (Table 1). A small part of the alpine Rhine basin is located outside the Swiss borders and the glaciers in this part are therefore not included in the analyses (0.3% of the glacier area of the Rhine basin). These four main river basins experience varying climates, with the Rhone and Danube basins being drier, and the Po basin generally wetter, compared to the Rhine basin.

Switzerland has extensive water management infrastructure, including reservoirs and water transfers, leaving only 14 catchments classified as predominantly natural. Additionally, streamflow data for 8 catchments were obtained from discharge measurements at water intakes with minimal influence from management infrastructure upstream. Thus, altogether, 22 catchments represent a natural streamflow signal.

3 Hydrological, meteorological and cryospheric data

For the glacio-hydrological characterization of 2022 and the comparison with past extremes, we assembled observations and model-based estimates of the various water balance terms (streamflow, precipitation, evapotranspiration, snowmelt, glacier mass balance) and temperature data for all of the catchments at a daily resolution. Since glacier mass balance is only available

Table 1. Characteristics of the four main studied basins in Switzerland, with the number of studied sub-catchments indicated in the last column. The Glacierization column refers to relative glacier cover for the chosen outlets in column 2, with in brackets the range for the sub-catchments. Glacier data refer to the Swiss Glacier Inventory 2016.

	Main outlet	Glacier area [km^2]	Glacierization [%]	sub-catchments [n]
Rhine	Basel	291.86	0.81 [0.10-27.67]	38
Rhone	Porte du Scex	585.67	11.14 [0.45-70.01]	35
Po	Bellinzona	34.76	0.16 [0.16-7.12]	8
Danube	Martina	48.98	2.47 [0.05-22.34]	7

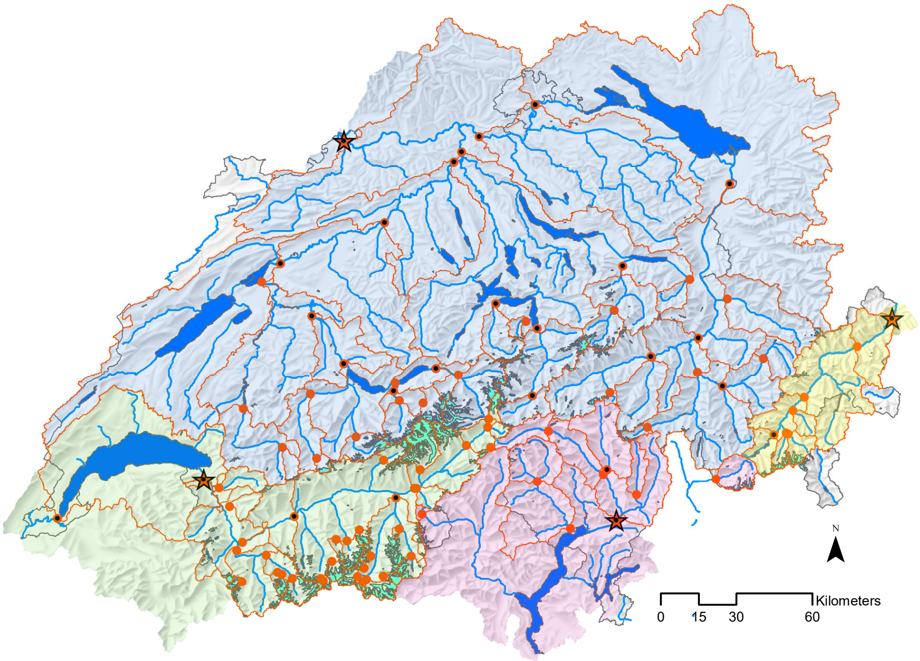

Figure 1. Map of hydrological Switzerland with the 88 studied catchments and gauging stations indicated (orange outlines and dots). The four main river basins are indicated with a background color (Rhine blue, Rhone green, Po pink and Danube yellow). Glacier outlines (turquoise) are from the Swiss Glacier Inventory 2016. Selected outlet stations for the main river basins (stars) and gauging stations with streamflow data starting before 1921 (black dots) are indicated.

for a few selected glaciers and at a seasonal resolution, a method was developed to estimate this for all individual glaciers in Switzerland at the daily scale (Section 4.1).

For streamflow, we used a combination of gauging stations from the network of the Federal Office for the Environment Switzerland (FOEN) (64 stations) (Höge et al., 2023) and stations from the Cantons of Bern (4), Valais (1), Glarus (1) and Vaud (1), as well as streamflow time-series from hydropower companies (Alpiq, Kraftwerke Mattmark AG, Forces Mortrices de Mauvoisin and Aegina SA). These time series varied in length and quality. The catchments were classified based on time series length and a water balance test to determine what types of analysis (e.g. investigation of glacier melt contribution to streamflow, year-to-year comparisons, or water balance calculations; see Section 4 and Table S1) the streamflow data could support.

The water balance test (details on data used provided below) evaluated the ratio of measured streamflow to the total of precipitation, evaporation, and glacier storage change. Catchments were included in the analysis if the ratio deviated by less than 25%. For deviations exceeding 25%, we followed these criteria: 1) if the ratio exceeded 1 and the catchment was classified as natural, we applied a uniform multiplication correction to the daily precipitation data, 2) if the ratio exceeded 1 and the catchment was classified as influenced, we excluded it from analyses involving precipitation estimates (assuming underestimation of precipitation) and 3) if the ratio was below 1, the catchment was used only for relative year-to-year comparisons, as absolute streamflow might be underestimated compared to the other water balance terms.

Catchment average daily time series of precipitation and temperature were obtained from the RhiresD (hydrological Switzerland) and TabsD (Switzerland) products from MeteoSwiss for the period 1961-2022 (MeteoSwiss, 2019, 2021). These are interpolated gridded datasets at a resolution of approx. 1 km. Some catchments covered parts outside of the (hydrological) boundary of Switzerland; these small areas were not taken into account for calculating catchment average values. To extend the time series further back in time (Section 4.4), we selected all Swiss meteorological stations that covered the period from 1900 until 2022. This resulted in 44 precipitation stations and 16 temperature stations (Fig. S1). The monthly and annual anomalies for these stations were averaged to obtain a single, long-term Swiss-wide time series of precipitation and temperature anomalies.

For evapotranspiration amounts (ET), model outputs from the distributed hydrological model PREVAH were used (Viviroli et al., 2009; Zappa and Kan, 2007; Höge et al., 2023). This model runs in an operational setting for Switzerland and data was available from 1981-2022. Evaporation is modelled following the Penman-Monteith scheme as detailed in (Gurtz et al., 1999) and (Zappa and Gurtz, 2003). Catchment boundaries excluding the glacier outlines from Swiss Glacier Inventory (SGI) 2016 (Linsbauer et al., 2021) were used to extract actual daily evapotranspiration values from the gridded model outputs

Information on snow water equivalent (SWE) was obtained from an operational snow product provided by the WSL Institute for Snow and Avalanche Research SLF for the period 1999 to 2022. This product consists of daily SWE maps for Switzerland and adjacent hydrological regions at a 1 km resolution. It is based on the assimilation of snow monitoring data from 349 stations into the snow model OSHD_TICL as described in Mott et al. (2023) and Magnusson et al. (2014). The SWE product is intended to represent seasonal snow, consequently all snow remaining on September 1 of each year has been removed from the simulations. Because only 12 snow monitoring stations are available above 2500 m a.s.l., catchment average SWE time series were extracted only for the non-glacierized catchment areas, equivalent to the treatment of the ET data. Snow on the glaciers is included in the glacier storage change data (Section 4.1). To use SWE as a proxy for snowmelt, the differences between maximum and minimum SWE within a specific time period (e.g., a month, season or year) were calculated.

For the extrapolation of available glacier mass balances in space and time, all the available annual and seasonal glacier mass balance data (GLAMOS, 2024) were used. The surveyed glaciers are a representative sample and cover all climatological regions of the Swiss Alps. The data refer to a fixed-date system (30 April for winter, and 30 September for annual mass balances) and comprise 28 glaciers in total (Table S2). Only 3 time series extend back to before 1920, while 9 time series start before 1970. The density of observations strongly increased after 2005, with 20 glaciers being measured in 2022. Geodetic mass balances for the period 1980-2010 was available for all glaciers in Switzerland (Fischer et al., 2015). Glacier outlines constrained the glacier area evolution over time, and included the glacier outlines from 2016 (Linsbauer et al., 2021) and 1973 (Müller et al., 1976; Maisch, 2000; Paul, 2003).

4 Methods

4.1 Swiss-wide daily glacier storage changes

To analyze glacier mass changes and melt and assess their downstream contributions to streamflow in time and space, a new approach was developed. It estimates glacier mass change at the scale of all individual Swiss glaciers (1400 glaciers) at a daily time resolution. The approach is based on a combination of in-situ measurements, remote-sensing data and modelling, and consists of four main steps: 1) extrapolating seasonal and annual mass balance from surveyed glaciers in space for obtaining an observation-based year-to-year variability, 2) combining these with geodetic mass balances from the comparison of digital elevation models (DEMs) for obtaining information on long-term mass changes of all individual glaciers, 3) extracting a seasonal daily glacier mass balance pattern from a daily glacier mass balance model constrained with these data sets, and 4) estimating glacier area evolution over time using area-volume scaling to convert specific mass balance into absolute glacier mass changes, or water volumes (Fig. S2).

For step 1, the available long-term glacier-wide annual mass balance measurement series (28 in total) were converted into a mass balance anomaly for each surveyed glacier g and year y ($\Delta B_{g,y}$). This was done by subtracting the mean of a glacier reference period, here 2011-2020 (GLAMOS, 2024; Huss et al., 2015). Taking the annual mass balance anomaly (ΔB) instead of absolute mass balance values is necessary for spatial extrapolation as glaciers are known to respond with strongly differing mass balances to the same change in atmospheric forcing, mostly depending on their geometry (Fischer et al., 2015; Brun et al., 2019). Long-term observations show that mass balance anomalies are more spatially homogeneous. The values $\Delta B_{g,y}$ for the set of surveyed glaciers were then extrapolated to all individual glaciers contained in the SGI2016 (Linsbauer et al., 2021) using an inverse-distance weighting scheme. The initial search radius for an individual glacier was set to 150 km, which was extended in steps of 10% until at least three measurements were available. The inverse-distance weighting also accounts for the main weather divide of the Alps by attributing higher weights to series on the same side (North/South of the divide) as the glacier to which the anomaly is extrapolated to.

Observed winter mass balances ($B_{\mathrm{w},g,y}$) were extrapolated based on their actual values (instead of their anomalies) using the same inverse-distance weighting scheme. 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). The correction was set to 10% per 100 m elevation difference, a value that is challenging to validate due to the limited availability of observational series informing about local-scale snow accumulation differences between neighboring glaciers.

For step 2, the extrapolated annual mass balance anomalies $\Delta B_{g,y}$ are superimposed onto the available geodetic mass balance $\overline{B_{geod,1980-2010}}$ (see Section 3) to obtain a locally adjusted, absolute annual mass balance $B_{g,y}$ for each individual glacier:

$$B_{g,y} = \overline{B_{geod-g,1980-2010}} + (\Delta B_{g,y} - \overline{\Delta B_{g,1980-2010}}). \tag{1}$$

Here, $\overline{\Delta B_{g,1980-2010}}$ is the mean of the mass balance anomalies for 1980-2010, which is used to correct for the bias between $\overline{B_{geod-g,1980-2010}}$ and the observed 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.

For step 3, 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. The model computes daily mass balance on a fine spatial grid that are then aggregated to glacier-wide cumulative time series. For each of these glaciers, model parameters are optimized to best match all available point-based winter and annual mass balances measurements, as well as geodetic surveys of multi-annual mass change. Next, each of the non-surveyed glaciers was assigned a simulated daily cumulative mass balance time series of the closest surveyed glacier. The daily cumulative time series were scaled to fit the assigned winter and annual mass balance of steps 1 and 2 according to

$$B_{g,d} = \begin{cases} B_{\mathrm{nearest},d} + \left(\frac{B_{\mathrm{w},g,y} - B_{\mathrm{w,nearest},y}}{\Delta t_{oct-apr}} \times d\right) & d \in [1, 212] \\ B_{\mathrm{nearest},d} + (B_{\mathrm{nearest},212} - B_{g,212}) & d \in [213, 243] \\ B_{g,243} + \left(\frac{B_{g,y} - B_{\mathrm{nearest},y}}{\Delta t_{jun-aug}} \times d\right) & d \in [244, 335] \\ B_{\mathrm{nearest},d} + (B_{\mathrm{nearest},335} - B_{g,335}) & d \in [336, 365] \end{cases} \tag{2}$$

in which $B_{g,d}$ is the daily cumulative mass balance at day d in m w.eq., expressed as number of days from 1st of October. $B_{\mathrm{nearest},d}$ is the simulated time series of daily cumulative mass balances from the closest surveyed glacier. Δt are the number of days for the months indicated in subscripts.

For step, 4, we combined linear interpolation and volume-area scaling as a simple method to estimate glacier area evolution. The glacier area is needed together with the specific glacier mass balance ($B_{g,y}$ and $B_{g,d}$) to calculate glacier mass change,

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and hence the generated meltwater volumes. 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 volume V by using volume-area scaling (Bahr et al., 1997):

$$A = (\frac{V}{c})^{\frac{1}{\gamma}}, \tag{3}$$

where c is a glacier-specific constant, and γ=1.8 is an exponent which was adjusted to fit the observed area changes. 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 ($V \pm \Delta V$) based on the extrapolated mass balance and glacier area of previous or next time step (depending on whether the equation is used for determine an area after 2016 or before 1973) and a volume-to-mass change conversion factor of 850 kg/m^2 (Huss, 2013).

Steps 1-4 were used to derive daily time series of cumulative mass balance (m w. eq.) and daily glacier storage changes (m^3/d w. eq.) from 1916 to 2022 for each individual glacier. Positive daily glacier storage change values represent net daily accumulation over the glacier, while negative values indicate net daily mass loss over the glacier. Time series from glaciers within the same catchment were averaged (mass balance) or summed (storage change) for further analysis.

4.2 Attributing extreme glacier mass loss

To attribute the extreme glacier mass change of 2022 to its causes, three aspects were analyzed: 1) the contribution of summer and winter mass balance anomalies to annual mass balance anomalies, 2) the timing and intensity of the summer melt period, and 3) the ratio between balanced and imbalanced melt contributions (Fig. S2). In this attribution framework, radiation terms were not physically analyzed, but rather its effects, such as earlier melt onset and stronger melting. For aspect 1, winter and summer balance anomalies were calculated based on the reference period 1991-2020. For the glacier attribution analyses, mass balance years were defined using the stratigraphic method, i.e. by identifying the period between the two successive annual minima of the cumulative mass balance time-series. The difference between these minima represents the annual mass balance. Winter mass balance is defined as the difference between the first minimum and the maximum cumulative mass balance during that year. Summer mass balance is the difference between annual and winter mass balance.

For aspect 2, we attributed the extreme melt of 2022 to differences in timing of the melt season and its intensity compared to the reference period (1991-2020). We calculated how much of the anomalous melt occurred due to (i) an earlier onset of the melt period, computed as the amount of melt occurring in the shifted timing of the maximum cumulative daily mass balance between 2022 and the mean of the reference period, (ii) more intense melting when compared to the reference summer mass balance period, and (iii) the timing of the melt season ending, computed here as the amount of meltwater generated between the mean end of the mass balance year in the reference period and the end of the mass balance year in 2022.

For aspect 3, the sum of all negative glacier storage changes over the mass balance year 2022 was separated into balanced and imbalanced melt. The balanced part of the melt equals the winter accumulation on the glacier. The remaining melt is the imbalanced melt and causes the glaciers to lose volume with respect to the start of the year. For each glacier and extreme year

(2022 and other years), the day when glaciers switch from balanced to imbalanced melt was extracted as the day when the cumulative daily mass balance equaled zero, similarly as the "Glacier Loss Day" in Voordendag et al. (2023).

4.3 Attribution of streamflow responses and glacier compensation effects

For the attribution of the 2022 streamflow anomalies (ΔQ), we analyzed anomalies in precipitation (ΔP), snowmelt (ΔS), ET (ΔET), and glacier storage change (ΔG). For each of these water balance components, annual (hydrological year) and summer (MJJA) anomalies were derived. May was included since in 2022, the month experienced high snow melt rates already. The anomalies were generally calculated using the reference period 1991–2020. However, due to insufficient data, ΔSWE was calculated using 1999–2020 across all catchments, while ΔQ was calculated for seven catchments using reference periods starting between 1994 and 2012. For ΔG, the sum of all storage change values (positive and negative values) were used.

The individual water balance anomalies were used to calculate a glacier compensation level L:

$$L = \frac{\Delta G}{-(\Delta P\ (+\Delta S) - \Delta ET)} \times 100\%. \tag{4}$$

L is a percentage indicating to what extent the extra glacier melt (surplus) could compensate for deficits in precipitation, snowmelt (only in summer), or increased evapotranspiration. A value of 100% means that the extra glacier meltwater could fully compensate for the deficits in the other water balance terms, thus resulting in close to normal streamflow ($\Delta Q = 0$).

Since the various water balance anomalies were derived from various data sources and estimation methods, the sum of all terms does not necessarily equal zero. To include this uncertainty in the estimation of L, we calculated the uncertainty ϵ as follows:

$$\Delta Q = \Delta G + (\Delta P\ (+\Delta S) - \Delta ET) + \epsilon. \tag{5}$$

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, and once to the water deficit drivers in equation 5. 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. Thus, in total, we derived three estimates of L per catchment, indicating the maximum range of possible values.

4.4 Long-term perspective: past extremes

To put the year 2022 in a long-term perspective, seven years with very negative annual and summer mass balances were selected: 1921, 1928, 1947, 1998, 2003, 2018 and 2022. All of these years where characterized by severe droughts (Zeng et al., 2005; Erfurt et al., 2019; Brunner et al., 2019; Hansel et al., 2022) and were compared in terms of meteorological conditions, glacier mass balance, glacier meltwater volume, and streamflow volumes. Since only one-third of the catchments have streamflow data covering all extreme years, an emphasis is put on the comparison between 2003 and 2022.

To gain insights into the changing glacier meltwater volumes over time, while correcting for temperature differences, a glacier melt sensitivity index $\Theta_{g,y}$ was defined as

$$\Theta_{g,y} = \frac{M_{g,y}}{T_{g,y}}, \tag{6}$$

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where $M_{g,y}$ is the sum of all negative glacier storage changes between 1st of June and 30 September for glacier g and year y, and $T_{g,y}$ is the average temperature in Kelvin (K) (to avoid issues with close to zero values) for the mean elevation of the same glacier and the same period. Yearly values of Θ_g were calculated for the period 1961-2022, corresponding to the data coverage of the gridded meteorological product (Section 3). To compare Θ_g across glaciers, time series of Θ_g were normalized between 0 and 1, based on the maximum and minimum values for each glacier.

5 Results

5.1 Attribution of extreme glacier melt in 2022

In 2022, all Swiss glaciers together lost a total estimated ice volume of around 3 km^3, equaling 2.6 km^3 of meltwater (Table 2. This amount is more than three times the mean glacier volume loss over 1991-2020. The glacier volume loss of 2022 equals to around 5.9% of the total inferred volume of all Swiss glaciers in 2021 (GLAMOS, 2024). The 2022 net annual meltwater volume loss (M_a) represents roughly 6% of the total precipitation of Switzerland in 2022 (1037 mm), while covering only 2.1% of the Swiss area. The total meltwater volume generated (net melt of 2.6 km^3 + balanced melt) was around 3.6 km^3, around 28% more than the reference meltwater volume. Daily glacier storage changes were highest during July, and deviating most from the reference period average during May, June and July (Fig. S5).

Meltwater volumes for the different basins scale with the glacierized areas and were highest for the Rhone basin (Table 2. In contrast, the area-weighted annual mass balance was most negative for glaciers in the Po and Danube basins, (~ -3.5 m. w.eq.) and least negative in the Rhine and Rhone basins (~ -3.1 m w.eq.) (Fig. S3).

The anomalous annual mass balance of 2022 (ΔB_a) was primarily related to the summer mass balance anomaly (ΔB_s) (Fig. 2a). For the different glaciers, the contribution of (ΔB_s) to ΔB_a varied between 55-75%. For glaciers in the Po and Danube basins, the winter mass balance anomaly (ΔB_w) contributed the highest among the basins and explained up to 45% of ΔB_a.

The anomalous summer mass balance and the generated summer melt volume could be attributed for 15-20% to the early onset of the ablation period and for 75-85% to the more intense melt over the summer period, with similar contributions of these two aspects across the glaciers in the different basins (Fig. 2b). The day of maximum cumulative daily mass balance (stratigraphic winter mass balance), was reached 1-3 weeks earlier in 2022 than in the reference period (not shown). The ablation season ended for approximately half of the glaciers (661/1400) not later than during the reference period. For the other glaciers, the melt season of 2022 ended 1-4 weeks later than during the reference period. Compared to the other two processes, the prolongation of the ablation season into autumn contributed only marginally to the extra glacier melt in 2022 for some glaciers in the Rhine and Danube basins.

Due to the limited snow accumulation, most of the total glacier melt in 2022 was imbalanced. For glaciers in the Danube and Po basins, 74-80% of the melt was imbalanced (Fig. 2c), which was higher than in the Rhine and Rhone basin, where the imbalanced melt ranged from 64% to 77%. Melt turned from balanced to imbalanced conditions between mid-June and mid-July. This point was reached slightly earlier for glaciers in the Danube and Po basins and some glaciers in the Rhone basin,

Table 2. Glacier meltwater volumes and mass balances for 2022 and the reference period (1991-2020). M refers to meltwater volumes, whereas B refers to glacier-wide mean specific mass balance. a refers to net annual, s to summer, w to winter and t to total. CH/Basin refers to Swiss-wide/Basin average or sum. The numbers refer to the mass balance year corresponding to the hydrological year; used in most of the comparisons and analyses. Table S3 shows the results for the stratigraphic mass balance, used in the glacier attribution analyses.

		2022	**Ref.**
M_a [km^3]	CH	2.58	0.82
	Rhine	0.73	0.26
	Rhone	1.62	0.46
	Po	0.09	0.04
	Danube	0.13	0.05
M_t [km^3]	CH	3.60	2.82
	Rhine	1.11	0.94
	Rhone	2.20	1.59
	Po	0.12	0.12
	Danube	0.17	0.17
B_a [m]	CH	–3.1	–0.8
B_w [m]	CH	+1.0	+1.2
B_s [m]	CH	–4.1	–2.0

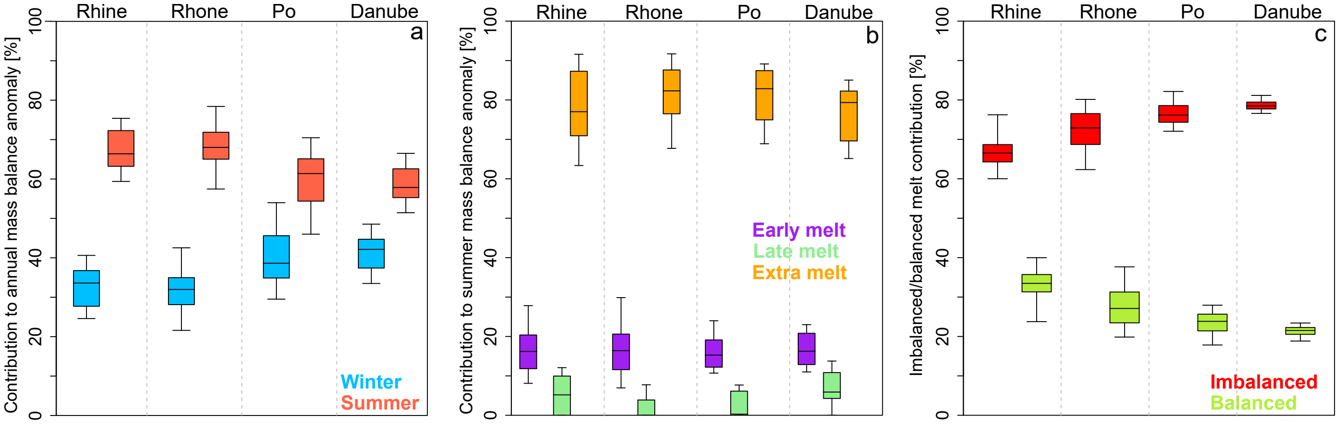

Figure 2. Attribution of extreme glacier volume change in 2022 to its mass balance components for all Swiss glaciers. a) Contribution of summer (ΔB_s) and winter mass balances (ΔB_w) anomalies to the annual mass balance anomaly ΔB_a, b) Contributions of the early onset of the melt season, late ending of the melt season and the intensity of the melt season to ΔB_s. c) Partitioning of total glacier meltwater volume into balanced and imbalanced melt. Each box-plot includes all glaciers in the respective main river basin.

followed by the majority of the glaciers in the Rhone and the Rhine basin (not shown). During the reference period the same point would occur for most glaciers in the first half of August. This is approximately 40 to 60 days later than in 2022.

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5.2 Attribution of 2022 streamflow anomalies

During 2022, the downstream reaches of the main river basins were severely affected by the dry and hot conditions (Fig. S4), resulting in a hydrological drought. For most catchments, streamflow showed large deficits, ranging from -60 up to -600 mm for the annual scale (variable "Q" in Fig. 3 and Fig. S4). The largest absolute deficits were reached for catchments in the Po, Rhone and Rhine basins with glacierization <5%. Over the summer, absolute streamflow deficits were smaller, while streamflow surpluses in highly glacierized catchments were larger, compared to the annual streamflow anomalies. The streamflow anomalies changed sign with increasing level of glacierization in the Rhine and Rhone basins, in which catchments span the full range of glacierization (Fig. 3).

Besides streamflow, the largest anomalies came from the precipitation and the glacier net storage change (variable "P" and "G" in Fig. 3), but with opposite signs. For snowmelt (variable "S" in Fig. 3), only the non-glacierized area was considered and therefore the absolute anomalies are smaller, especially for catchments with high glacierization. During summer, the lack of precipitation (rainfall) and the snowmelt deficit of the non-glacierized area contributed approximately equally to the water deficit for most catchments. The surplus glacier net storage change counterbalanced the deficits in rainfall and snowmelt. The glacier net storage change anomalies were larger at the annual scale than for the summer, especially in the Rhone and Danube basin, which is opposite to the total glacier net storage change value (not the anomaly), which is larger in summer (mostly ablation) than over the year (net effect of accumulation and ablation). The lack of snow, in addition to the high melt, caused these larger anomalies at the annual scale than for the summer. The net glacier storage change anomalies (surpluses) increase with increasing glacierization. The smallest water balance anomaly is the evapotranspiration anomaly (variable "ET" in Fig. 3). For catchments in the Rhone basin the ET anomaly was even negative, indicating a water-limited situation in this part of Switzerland. Largest evapotranspiration anomalies were found in the Danube basin.

5.3 Glacier compensation effects and contributions to streamflow

The large glacier melt anomalies of 2022 could (partly) compensate for the lack of precipitation and snowmelt, as well as for the extra evapotranspiration. The degree of this compensation depends on the level of glacierization (Fig. 4). At the annual scale, in catchments with around 25% glacierization the extra glacier melt could fully compensate the deficits in the other water balance terms ($L =$100%), while in summer this full compensation already occurs for catchments with 15-20% glacier coverage (Fig. 4). For catchments with higher glacierizations, resulting in $L >$ 100%, the excess glacier melt overcompensated the negative anomalies in precipitation, snowmelt and evapotranspiration, leading to positive anomalies in streamflow. A 50% compensation of the water deficits occurred for catchments with a glacierization of 15-20% (10-15%) at the annual (summer) level. Even for catchments with only a few percent glacier cover (1-5%), the extra glacier melt could still alleviate the impact of the deficits by around 10%. The addition of the water balance anomaly rest term ϵ (difference between the ΔQ and the sum of ΔP, ΔS,ΔET and ΔG) leads mostly to a higher compensation level for catchments with low glacierization, and vice versa.

The anomalous glacier melt in combination with the precipitation deficits of 2022 resulted in much higher relative glacier melt contributions to streamflow compared to the reference period (Fig. 5a-c). At the annual scale, imbalanced glacier melt

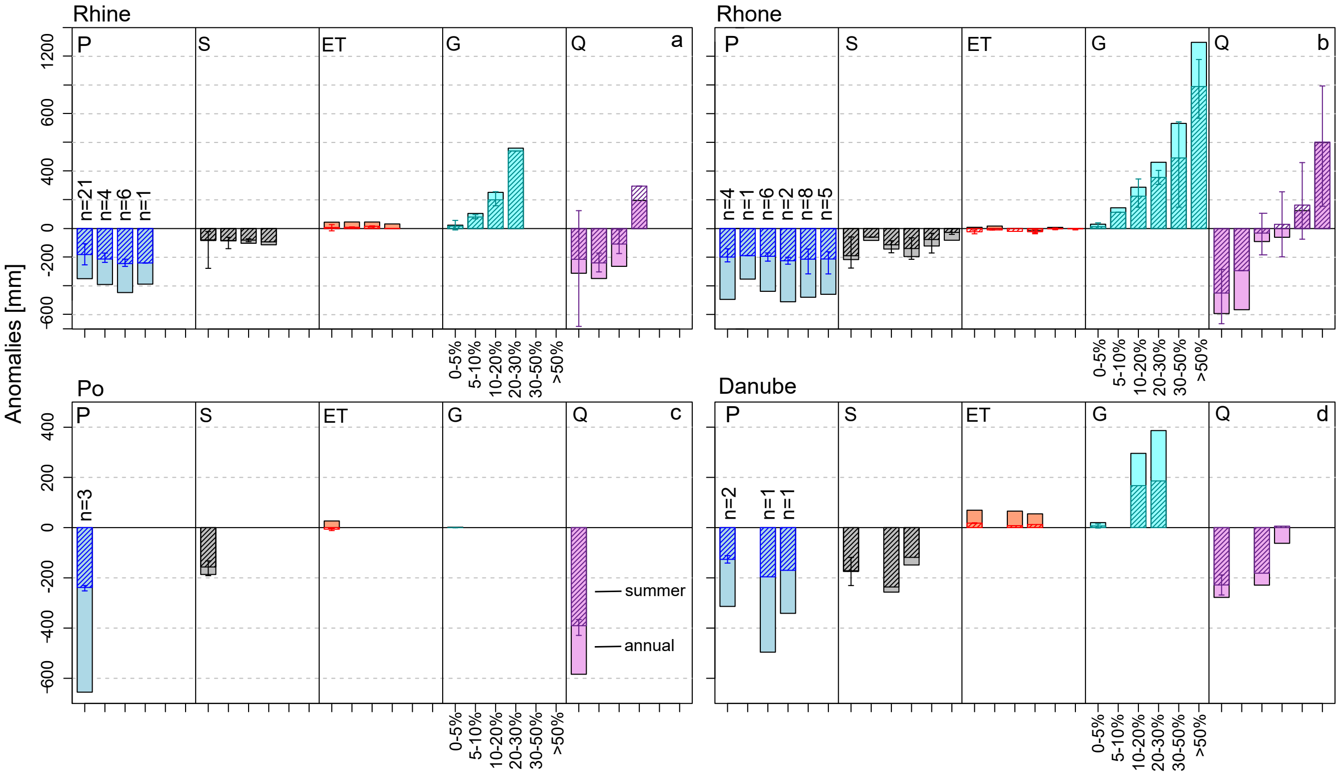

Figure 3. Water balance anomalies in 2022 specified for catchments with different glacierization. Within each of the four main basins, anomalies are shown for: (1) total catchment precipitation P, 2) snowmelt S from non-glacierized catchment areas, (S is part of P at the annual scale), 3) Evapotranspiration ET, 4) Glacier storage change G (net storage change over the year or summer) and 5) streamflow Q). Anomalies are aggregated by catchment glacierization classes (indicated below the variable G). n is the number of catchments within each glacierization class. The filled bars indicate the annual anomalies (Oct-Sep) while the dashed bars show the summer anomalies (May-Aug). Whiskers show the range for summer anomalies. All variables are expressed in mm with respect to the entire catchment.

contributed between a few percent up to 60-80% of annual streamflow volumes (Fig. 5a). This imbalanced glacier melt is the part of the water supply that would be lost when glaciers have disappeared.

In summer, relative contributions of glacier melt were even higher, up to almost 100% of the summer streamflow for some catchments (Figure 5c). In particular, summer glacier melt contributions are disproportionally higher per unit of glacier cover for catchments with <10% glacierization (Fig. S7).

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.

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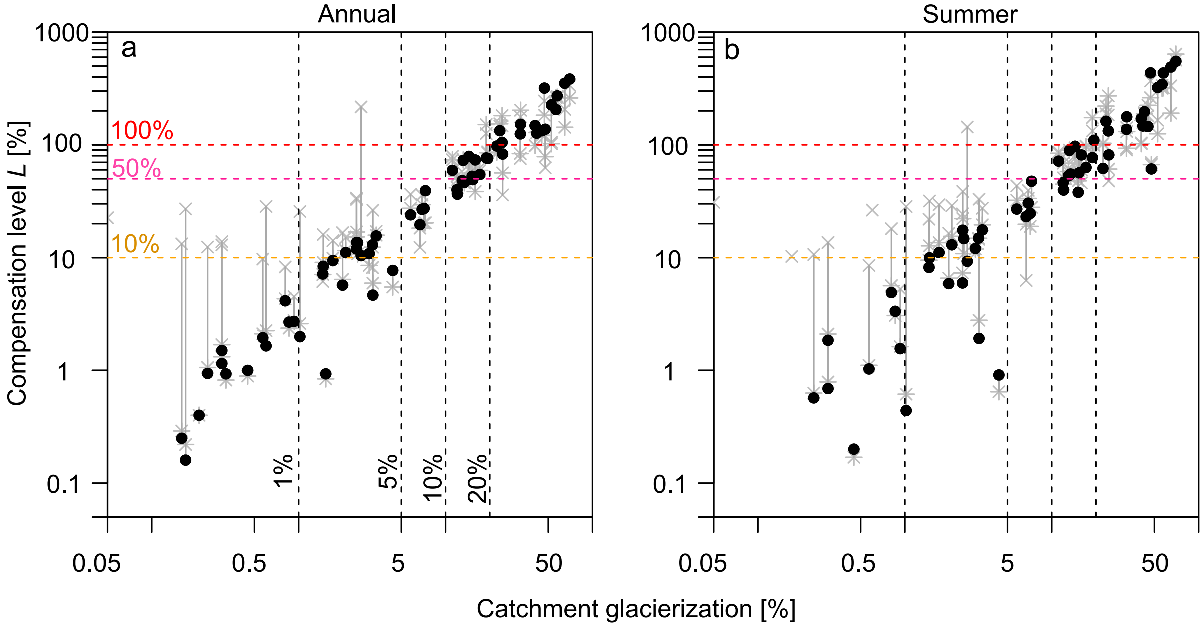

Figure 4. Glacier compensation level L against glacierization for annual (left) and summer (MJJA; right) periods. The gray bars indicate the range of uncertainty in L due to non-closing water balance anomalies of some catchments. Since the uncertain term in the water balance is not known, the crosses indicate the water balance anomaly rest-term added to glacier surplus term, and the asterisk indicate L when the rest term is added to deficit terms (Section 4.3). Note, the x- and y-axis are logarithmic.

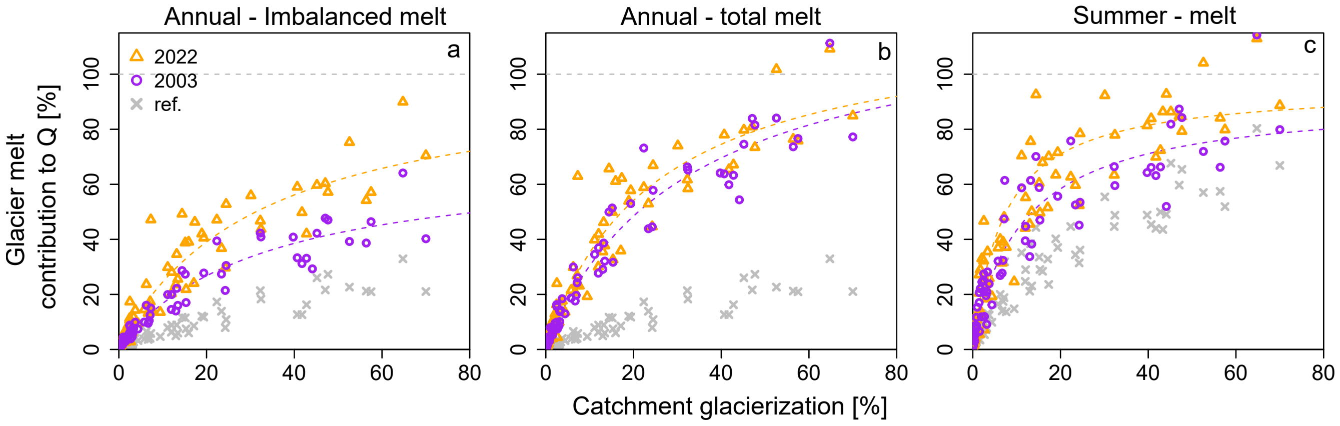

Figure 5. Glacier storage change contribution to streamflow in 2022, 2003 and during the reference period (1991-2020) for imbalance melt at the annual scale (a), for total melt at the annual scale (b) and for melt during summer (MJJA) (c). The dashed line shows an exponential fit between catchment glacierization and glacier melt contribution to streamflow.

5.4 Extreme melt of 2022 in a long-term perspective

2022 was a record year regarding annual and summer glacier specific mass balance (Table 3, columns 2-3) in the >100-year series of observation-based glacier mass balances for Switzerland. At the Swiss scale, only 1947 comes close to the extreme of 2022 in terms of annual glacier mass balance. In terms of meltwater volumes, the ranking of extreme years shifts, with 2022 no longer being the most extreme year (Table 3, columns 5-6). Between 1921 and 2022, the area of Swiss glaciers changed considerably, with an estimated area loss of 42%. Thus, the larger glacierized areas in the extreme years 1921, 1928 and 1947 resulted in substantially higher glacier meltwater volumes than in 1998, 2003, 2018 and 2022, especially in terms of total meltwater volumes, as opposed to net meltwater (mass loss) volumes.

Zooming in to the more recent extreme years (1998, 2003, 2018 and 2022), 2003 and 2022 were most extreme in terms of summer glacier mass balances and meltwater volumes. In terms of winter mass balance, 2003 and 2018 were more similar, with more snow accumulation than in 1998 and 2022. From all these recent years, 2022 had the highest net volume loss (M_{a}). However, the total glacier melt volume (sum of all daily negative storage changes) in 2022 was smaller than in 2003, despite higher specific melt (M_{t}, Table 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. 6 rows 2-3).

In terms of streamflow, the lowest flows of 2022 had never been that low at the outlets of the four basins, but for the Rhone basin (Table 3, columns 7-10). Compared to 1928, 1947, 2003 and 2018, the lowest flows of 2022 occurred earlier in the year, already in the second half of August for the Rhine, Po and Danube basins. Overall, annual and June, July and August streamflow were lowest in 2022 compared to the other extreme years, especially when focusing on the years 1998, 2003 and 2018 (Fig. 6, rows 4-7).

Despite strong negative precipitation anomalies in July of 1921 and 1928, comparable to the ones in July 2018 and 2022, these months had among the highest flows of the extreme years. This may be explained by 1) the high glacier meltwater volume contributions and 2) the absence of reservoir effects for these early extreme years. The only headwater catchment with long-term data and without reservoirs is located in the Rhine basin. Here, 2022 had the lowest annual and August streamflow (Fig. 6, row 4). For July, 2022 resulted in higher flows compared to 2018, possibly related to the high July melt volumes, leading to stronger compensation effects.

Relative glacier meltwater contributions to streamflow were among the highest in 2022, in particular in comparison to the more recent extreme years (Figure 6, rows 4-7). For catchments in the Po and Danube basins, where glacier meltwater volumes were smaller in 2022, the constant or increasing relative contributions highlight the continued importance of glaciers during droughts, even as overall meltwater volumes decline. Relative glacier meltwater contributions to streamflow peaked in July 2022, with a few percent at the outlets of the Po and Danube basins, and around 30% for the Rhine at Basel, and close to 100% for the Rhone at Porte du Scex. These contributions strongly diminished at the annual scale, but are still substantial for the Rhone basin (40%).

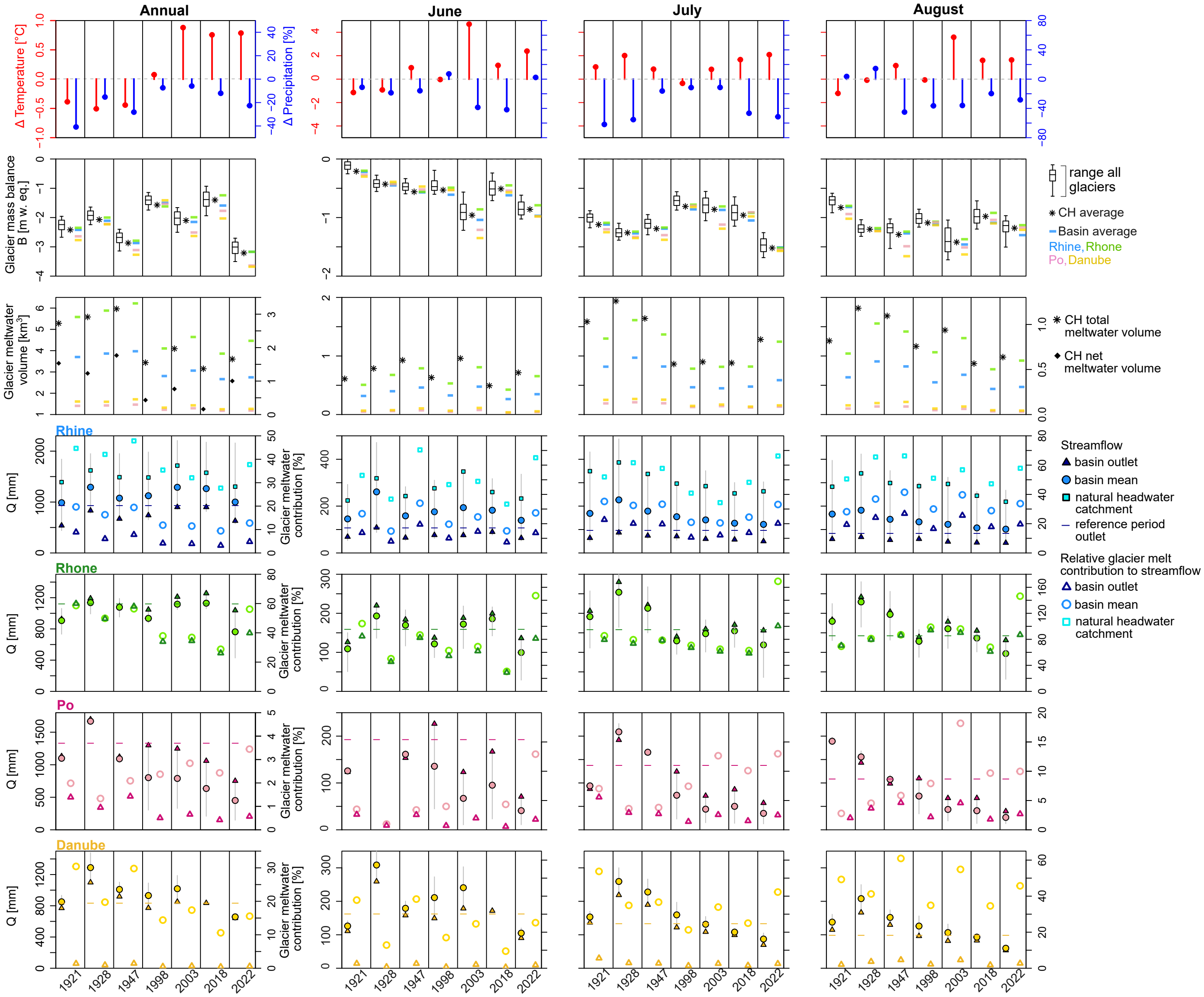

Figure 6. Comparison of meteorological, glaciological and hydrological conditions for glacio-hydrological extreme years (1921, 1928, 1947, 1998, 2003, 2018, 2022). The columns indicate different aggregation periods: annual and monthly (June, July, August), while the rows indicate different variables: temperature and precipitation anomalies (row 1), glacier specific mass balance (row 2), glacier meltwater volumes (row 3), streamflow (row 4-7), relative glacier meltwater contributions to streamflow (row 4-7). In each panel, the columns refer to the different extreme years. Note the double y-axes for row 3-7. The right y-axes in row 3 refers to the basin volumes, whereas the left y-axis refers to the Swiss-wide volumes.

Table 3. Glaciological and hydrological characteristics of selected extreme years, referring to the hydrological year (Oct-Sep). A_g is the glacier area, B_a, B_w and B_s the annual, winter and summer mass balances (m w.eq.), respectively, for the fixed system. M_a is the corresponding net meltwater volume and M_t the total meltwater volume (km^3 w. eq.), taken as the sum of all daily negative storage changes. The last four columns indicate the 7-day average lowest flow at the outlet of the four main basins (Fig. 1), with in brackets the date of occurrence and the rank for that day (rx).

	A_g	B_a	B_w	B_s	M_a	M_t	Rhine	Rhone	Po	Danube
	[km^2]	[m]	[m]	[m]	[km^3]	[km^3]	[m^{3}s^{-1}]	[m^{3}s^{-1}]	[m^{3}s^{-1}]	[m^{3}s^{-1}]
1921	1430	–2.4	0.4	–2.8	–3.43	–5.28	514 (1-5 r1)	49 (3-5 r1)	34 (1-5 r7)	21 (4-5 r5)
1928	1435	–2.1	1.3	–3.4	–3.01	–5.58	674 (29-9 r43)	101 (24-5 r2)	34 (30-9 r22)	42 (30-9 r62)
1947	1347	–2.9	1.0	–3.9	–3.91	–5.96	489 (30-9 r2)	167 (30-9 r74)	26 (20-9 r7)	41 (8-9 r10)
1998	1092	–1.6	0.9	–2.6	–1.75	–3.47	669 (19-8 r1)	102 (3-5 r26)	31 (30-8 r7)	33 (21-9 r12)
2003	1053	–2.1	1.4	–3.5	–2.21	–4.09	431 (24-9 r1)	149 (30-9 r54)	21 (18-9 r1)	24 (14-9 r1)
2018	907	–1.4	1.6	–3.0	–1.27	–3.15	522 (20-9 r3)	173 (9-9 r22)	23 (29-9 r4)	25 (30-9 r5)
2022	827	–3.1	1.0	–4.1	–2.56	–3.60	446 (14-8 r1)	118 (24-9 r10)	18 (28-8 r1)	24 (2-9 r1)

To closely analyze the possible decline of glacier meltwater supply (i.e. the declining phase of glacier peak water) during extreme years and its downstream consequences in a catchment-by-catchment comparison, we isolated a period during which 2022 was more extreme in terms of melt conditions than in one of the other recent extreme years, which was in July. We compared this with July 2003, as the more than 20 year difference between these extremes allows for analyzing the impact of glacier retreat. 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. 7). 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. 7). Even though meltwater volumes were higher here, not everywhere this led also to higher streamflow volumes ("Q" in Fig. 7). 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) that did not relate to higher glacier meltwater volumes. In all the other catchments, the higher meltwater volumes could not compensate for the higher precipitation deficits and less snowmelt ("S") in 2022 compared to 2003 and thus resulted in less streamflow. Alternatively, for catchments downstream of reservoirs and dams, more water may have been stored in the reservoirs in 2022 than in 2003.

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. S8). In the remaining catchments (located in the eastern part of Switzerland), 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, underscoring the important role of snowmelt for streamflow. The combination of higher glacier meltwater volumes and lower streamflow in 2022 compared to 2003 led to overall higher relative glacier melt contributions to streamflow (Fig. 5).

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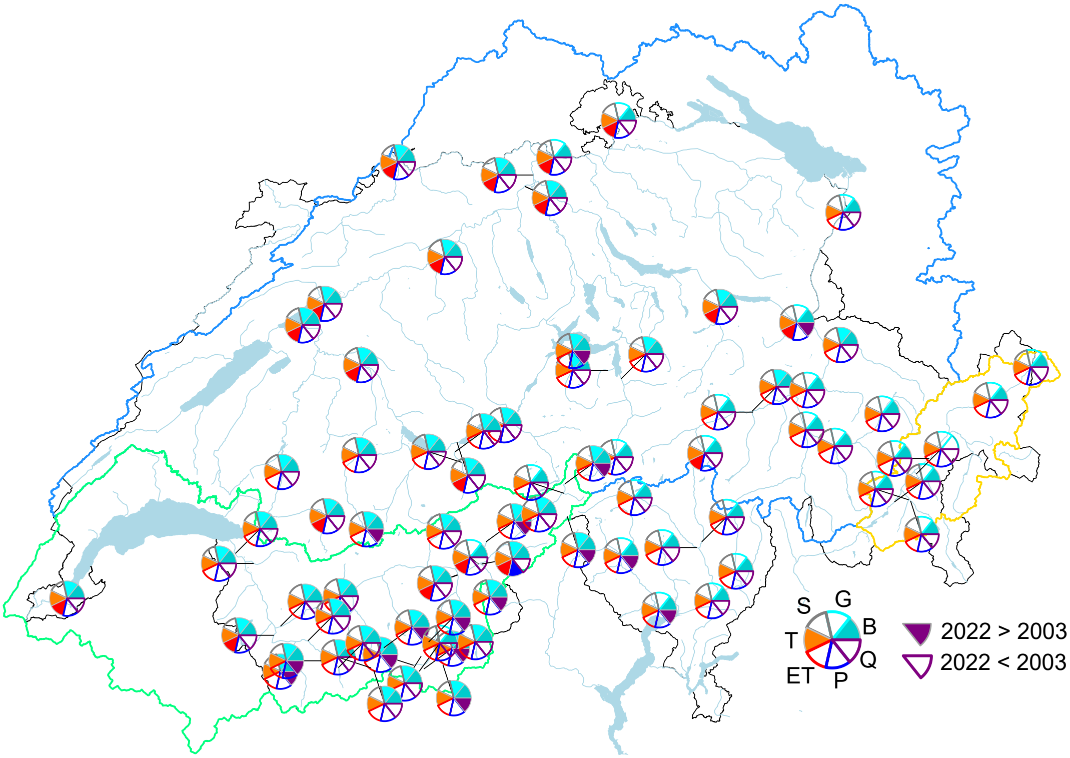

Figure 7. Comparison of glacio-hydrological variables in July between 2003 and 2022 at the catchment scale (76 catchments). Closed pie parts indicate that a given variable was higher (more (melt) water or warmer) in 2022 than in 2003, and vice versa for the open pie parts. T refers to the positive degree day sum, S to the change in SWE over July as proxy for snowmelt, G to the glacier meltwater volume, B the specific glacier melt rate (mass balance), and ET, P, and Q refer to the sum of evapotranspiration, precipitation and streamflow, respectively. Plots for June, August and summer (MJJA) can be found in the SI.

The spatially aggregated (catchment/basin) results indicate that glacier melt volumes are declining overall and for specific basins and catchments, despite stronger glacier melt rates (Table 3, Fig. 6 and Fig. S8). However, the various comparisons also show that for individual months or individual catchments, melt volumes in 2022 were still high in comparison to recent extreme years. To analyze the causes of this spatial variability, we analyzed the changing sensitivity (Θ) for all glaciers over 1961-2022 (Fig. 8). Years with common high Θ across all glaciers, 1983, 1991 and 2003, corresponded to years with more negative summer mass balances than the reference period average. After 2003, most glaciers smaller than $0.1\,\mathrm{km}^2$ did not show a high Θ value anymore, also not in 2022. For larger glaciers, especially $>10,\mathrm{km}^2$ 2022 still had a high sensitivity, thus responding to the high temperatures with high meltwater volumes.

Thus, large glaciers still responded with large melt volumes to the extreme meteorological conditions of 2022. Overall, around 40%/30% of the glaciers had larger annual net/total meltwater volumes in 2022 than in 2003. For the glaciers larger than 10 km^2 almost all glaciers had in 2022 higher net meltwater volumes losses, whereas this was only the case for 1/3 of

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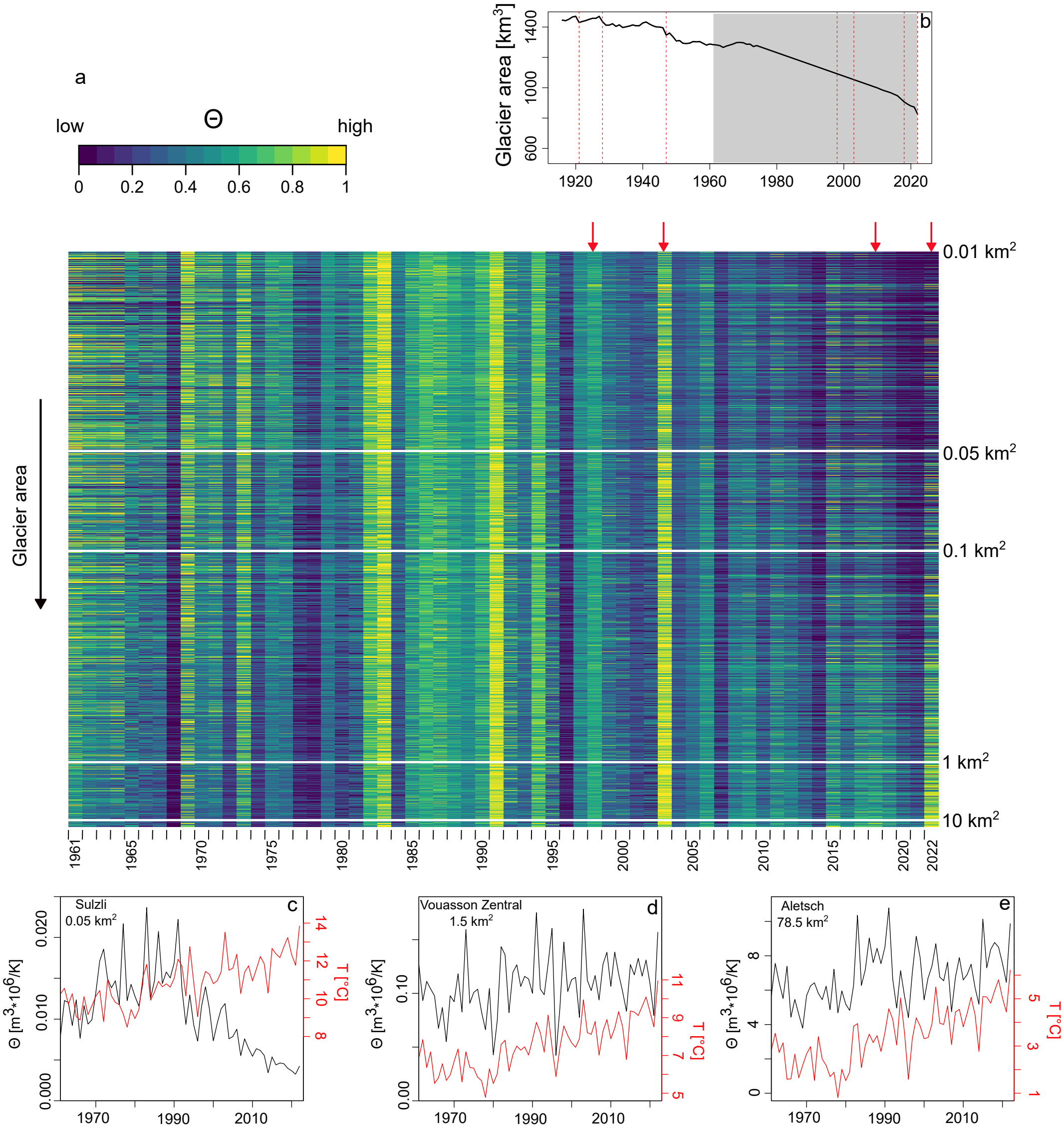

Figure 8. Time series of glacier melt sensitivity (Θ) for each glacier and the period 1961-2022, sorted by glacier area (a). panel b shows the evolution of the total glacier area in Switzerland over time, with in gray the period covered by the sensitivity metric of panel a. Panels c-e show examples of individual glaciers with Θ in black and temperature in red, with Sulzli glacier located in the eastern part of the Rhine basin, Vouasson glacier in the southern part of the Rhone basin and Aletsch in the northeastern part of the Rhone basin

the large glaciers for the total meltwater volume. For glaciers between 1-10 km^2, 75%/30% had higher net/total meltwater volumes, which further reduced to 45%/30% and 15%/2% for glacier size classes 0.1-1 km^2 and 0.05-0.1 km^2, respectively.

6 Discussion

6.1 The changing importance of glacier melt during drought

The analyses have shown that glaciers played a crucial role in sustaining downstream water supply during the extreme warm and dry year of 2022 in Switzerland. This confirms findings of earlier studies, showing for example that the imbalanced melt contribution of glaciers was relevant for reservoir filling during the Megadrought in Chile (McCarthy et al., 2022a), or that the importance of glacier melt contribution during droughts diminishes downstream in a non-linear way (Huss, 2011; Mastrotheodoros et al., 2020). Despite modest annual glacier melt contributions at downstream locations (for example at Basel we estimated 0.7% annually, 4.4% in summer), glacier melt becomes of notable importance on shorter timescales (Stahl et al., 2016; van Tiel et al., 2023), with contributions up to 20% in July and August 2022 at Basel (Figure 6). The analyses conducted here allowed us to quantify for the first time the compensation role of glaciers at a regional scale based on observations, providing insights how much glacier meltwater surpluses can counterbalance water deficits due to a lack of rainfall and snowmelt and increased evapotranspiration.

Although glacier melt was still of high importance in 2022 in Switzerland, the role of glaciers during drought is inevitably diminishing due to ongoing atmospheric warming and resulting glacier retreat (Zemp et al., 2015; Hugonnet et al., 2021). The results show declining meltwater volumes, particularly for small glaciers (Fig. 8, with clear spatial patterns at the catchment scale (Fig. 6 and 7). The various comparisons have shown that it is important to make the distinction between net annual meltwater volumes (mass losses) and total meltwater volumes when investigating a "decreasing glacier meltwater supply". While the net mass losses were higher in 2022 than in other recent extreme years, total melt water volumes were lower. This suggests that the reduction in glacier area has become more dominant than the increase in melt rates. The analyses here focused on specific extreme years, but fit in with longer-term trends (Fig. 9). Apart from the Rhone basin, all basins show a declining trend after 1980 for the total meltwater supply. For the Rhone basin, the lower meltwater volumes of 2022 than in 2003 may be a pre-cursor of a declining trend in the next years. The net meltwater volumes still show generally increasing trends in all basins, especially due to the record breaking 2022 year (Fig. 9). The total meltwater volumes are most relevant in a drought buffering context, as it is the meltwater supply of glaciers that drives this role and compensates for the lack of snow accumulation and precipitation during drought. We therefore chose this variable to analyze the change of meltwater supply during extreme years.

While the focus is on the changing glacier meltwater supply, we have shown that for the role of glaciers during droughts, it is important to look at other hydrological processes too, notably streamflow dynamics and relative melt contributions. Together (glacier melt and the resulting streamflow) ultimately determine when and how the importance of glaciers during droughts is going to significantly diminish.

Overall, we took here an "extreme year and drought" perspective to analyze the process of changing glacier meltwater supply, to focus on those years where glacier melt is most important downstream. Although this approach circumvents the question

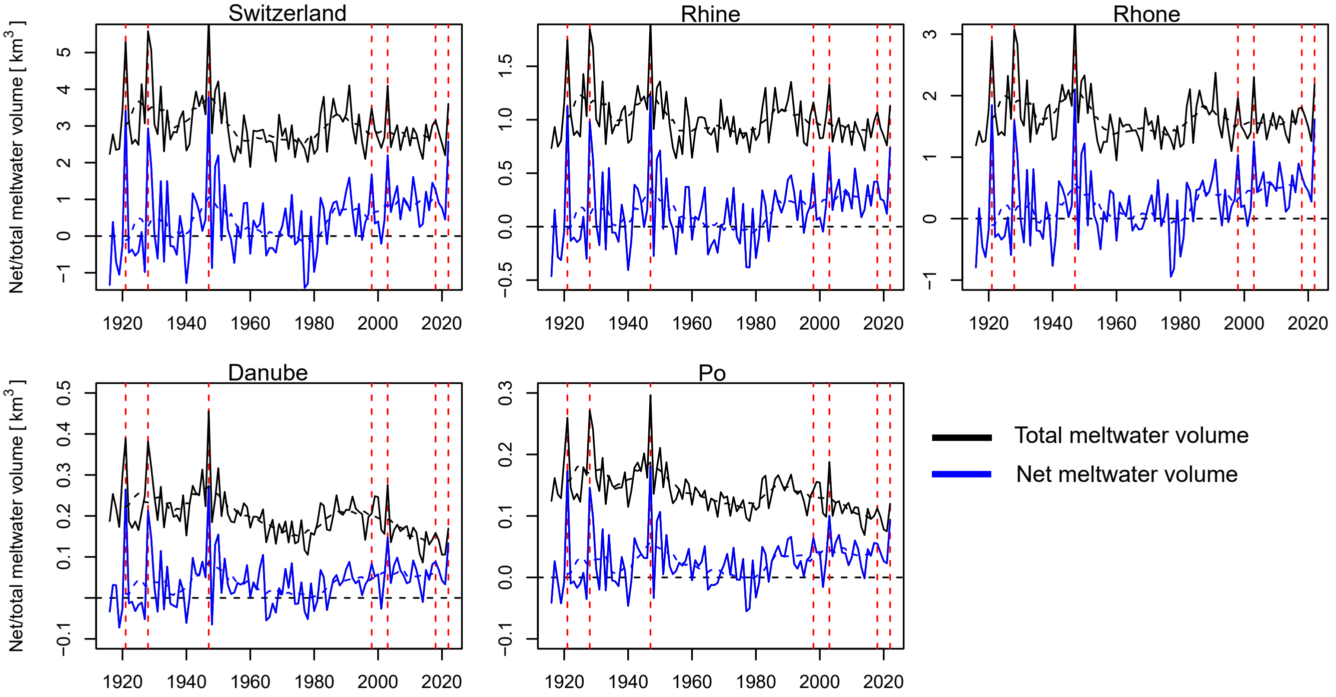

Figure 9. Evolution of annual meltwater volumes from 1916-2022 aggregated for Switzerland and the four main basins Rhine, Rhone, Danube and Po. The lines depict net meltwater volumes (annual glacier mass loss) and total meltwater volumes (absolute value of sum of all negative storage changes), with the 11y moving average as dashed line. Negative net meltwater volumes indicate mass gain of the glaciers. Vertical dashed lines indicate the selected extreme years.

of which inter-annual variability needs to be smoothed out in a peak water analyses (e.g. Huss and Hock, 2018) (Fig. 9), the comparability of the different extreme years is still challenging. To circumvent the comparability issue, Θ was introduced, which normalized the meltwater volumes to average summer temperatures. However, a changing Θ may not only relate to decreases in glacier area, but also to changes in glacier surface albedo, due to changing snow cover duration or the deposition and accumulation of dust at the surface (e.g. Gabbi et al., 2015). For example, 2022 was characterized by several Saharan dust events, accelerating the snowmelt on- and off the glacierized areas (Réveillet et al., 2022; Abegg and Mayer, 2023). Furthermore, also the thickening of supra-glacial debris (McCarthy et al., 2022b) or changes in shortwave radiation (e.g. Huss et al., 2009) is impacting the relation between air temperature and melt rates. Quantifying the effect of these additional processes would require detailed follow-up studies including energy balance modelling.

6.2 Uncertainty in water balance components

The study combined several data sources and approaches to estimate all terms of the catchment water balance. Because of this combination, the various terms are not necessarily consistent with each other, highlighting the challenges of obtaining data in high mountain terrain or over large regions where water management strategies play a significant role.

For precipitation, there is is general tendency of underestimating it at high elevations, due to the lack of meteorological stations there (Immerzeel et al., 2014), for example Gugerli et al. (2020) showed that precipitation on a few selected Swiss glaciers needed a correction factor between 2.2-3.7 to match on glacier SWE measurements. 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. SWE, here used as a potential for snowmelt, experiences similar uncertainties as precipitation. Moreover, by taking changes in SWE as proxy for snowmelt available to streamflow, we neglect sublimation processes and recharge processes to deep groundwater. Evapotranspiration is difficult to measure over large areas and was therefore derived from model simulations. There is only very little information on ET amounts at high elevations, and studies have shown high spatial variability especially under drought conditions (Mastrotheodoros et al., 2020).

The non-closing water balance issues could also arise from the glacier storage change estimations. Although the extrapolation procedure was 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. In particular, there is limited information on the spatial variability of accumulation and ablation processes. In addition, the evolution of the glacier area over time is a crucial element for determining the meltwater volumes, but also here only sparse observations in time exist. Whereas model simulations may include more local information than the presented extrapolation procedure, model parameters still need to be calibrated on the sparse measurements and transferred to unobserved glaciers.

Last, the measured streamflow data is a source of uncertainty too. Although the relative 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, these influences on the analyses can only implicitly be taken into account, for example by providing a range of compensation levels in Fig. 4 that include the possibility of water being im- or exported to/from the catchment. The role of human influences, in particular during extreme years such as 2022, on streamflow dynamics downstream of reservoirs in relation to glacier melt processes should be an avenue of future research (Brunner, 2021).

6.3 Outlook to future extreme years

The comparison of the year 2022 with other extreme melt years in the (recent) past showed both declines (2022-2003) and increases (e.g. 2022-2018) in the amount of meltwater that glaciers can generate to sustain downstream dry conditions. The direction of change depends both on the difference in extremeness (the specific glacier mass balance or melt rate) and the change in glacier area between two extreme years. When comparing 2022 to 2018, glacier area changes were relatively minor due to the short interval. However the higher melt rates of 2022 allowed for higher meltwater volumes. When comparing 2022 to the most recent year with exceptional high meltwater volumes (2003), almost all glaciers (950/1400) showed total meltwater volumes that could not reach the volumes anymore that were generated in 2003, despite mostly stronger melt rates. This change in balance between increased melt rates and glacier retreat was reached more widespread for the summer than for July (Fig. 7 and Fig. S8). Due to the stronger melt anomaly of July 2022 compared to July 2003, the melt was better able to offset the effect of strongly reduced glacier area. How future extreme years may evolve thus depends on the extremeness of future conditions and the timing, determining the interval for glacier area changes.

At the same time, comparing the glacier meltwater volumes with downstream water deficits, shows that these processes are in a delicate balance with each other. Similar processes, such as a lack of snow in winter, result both in increased glacier melt volumes (i.e. more to compensate with), but also stronger deficits in the non-glacierized parts of catchments (i.e. more to compensate for). With retreating glaciers this balance is shifting, with deficits increasingly becoming more dominant over glacier melt surpluses. Thus, for understanding the future role of glaciers as drought buffers, not only the absolute meltwater volumes are relevant, but also the changes in the other hydrological components. To better understand how future extreme meteorological conditions and consequent droughts may evolve, insights could be gained from large ensemble datasets of future climates Van der Wiel et al. (2019); Maher et al. (2021). Such scenarios, however, are still only available at rather coarse resolution. Still they could be used to force a glacio-hydrological model with updated future glacier geometries to analyze the balance between high glacier melt rates, glacier retreat and precipitation deficits on streamflow.

7 Conclusions

This study analyzed the role of glaciers during the drought year 2022 in Switzerland. We estimated daily glacier storage changes for all glaciers in Switzerland and brought it together with hydro-climatological data from 88 glacierized catchments. The findings highlight the critical role of glacier melt in mitigating water shortages during extreme dry and hot years.

In 2022, the glacier melt season began about two weeks earlier than usual, driven by snow deficits in winter and record-high temperatures in May. By mid-June, glaciers started melting in an imbalanced way, summing up to 80% of all melt that was unsustainable. The extra glacier melt that was generated over the warm and dry summer, particularly in July, could fully compensate the precipitation deficits at a catchment glacierization level of 15% and at least half of the deficit for catchments with a glacierization of 10%. These catchments are mostly located in the upstream parts of the Rhone, Danube and the Rhine basins. For catchments with smaller glacieriziation, annual and summer streamflow were strongly below average. The streamflow deficits were mostly driven by precipitation deficits, rather than increased evapotranspiration. For the summer period (MJJA) we estimated the lack of rainfall and the lack of snowmelt in the non-glacierized area to contribute to the overall water deficit with a similar magnitude.

While 2022 showed the highest relative glacier melt contributions to streamflow when comparing to other extremes (1921, 1928, 1947, 1998, 2003, 2018), the compensation and buffering role of glaciers is weakening as glaciers further retreat. A comparison with 2003, the most similar recent extreme year, shows that while 2022 had the most negative specific glacier mass balance (annual and summer), 2003 provided more total meltwater volume, due to a loss of glacier area between 2022-2003 of approximately $200\,\mathrm{km}^2$. Only 25% of the catchments still experienced higher meltwater volumes in the summer of 2022 than in 2003, a number that increased to 60% for July 2022 because of the more extreme melt rates in that particular month. Around half of the catchments showed declining meltwater volumes during summer, despite more extreme melt rates, for the 2022-2003 comparison.

Sensitivity analysis indicates that only the largest glaciers (>10 km^2) and about half of medium-sized glaciers (1–10 km^2) remain highly responsive to temperature increases and extremes. Altogether, the results indicate that for most smaller Swiss glaciers and around half of the catchments, meltwater contributions during droughts have started to decline. However, these results need to be confirmed in a longer-term future perspective including all years, not only extreme years. Despite these declines, the relative importance of glacier melt in streamflow has not diminished significantly and even increased, underscoring the ongoing, though diminishing, role of glaciers in buffering drought impacts.

The findings show the importance of analyzing extreme years from a holistic glacio-hydrological perspective for aiding conclusions on the declining glacier meltwater supply with ongoing glacier retreat. Furthermore, the findings underline the need to adapt future water management strategies to account for reduced meltwater availability in the future, in particular during droughts.

8 Data availability

Meteorological data are available through MeteoSwiss and through IDAweb (https://www.meteoswiss.admin.ch/services-and-publications/service/weather-and-climate-products/data-portal-for-teaching-and-research.html). FOEN streamflow data is available through https://www.hydrodaten.admin.ch/en/seen-und-fluesse/messstationen-zustand. The evapotranspiration data is available from Höge et al. (2023). Snow water equivalent data can be obtained through the institute of Snow and Avalanche Research (SLF) Davos. Glaciological data is available through GLAMOS. The daily glacier storage data for all glaciers in Switzerland will be made available in an online repository upon publication.

Competing interests

The authors declare no competing interests

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Author contributions

MvT designed the study and assembled all data. MH developed the extrapolation method for daily scale glacier storage changes for all Swiss glaciers, with input from MvT, and performed the calculations for all Swiss glaciers. MZ provided simulated ET data for all catchments and TJ provided the simulated SWE product for Switzerland. MvT conducted the analyses with feedback from DF and MH, designed the figures with input from DF, and wrote the manuscript. DF and MH edited the manuscript, while all authors provided feedback on the manuscript.

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References

Abegg, B. and Mayer, M.: The exceptional year of 2022:“deathblow” to glacier summer skiing in the Alps?, Frontiers in Human Dynamics, 5, 1154 245, 2023.

Alizadeh, M. R., Adamowski, J., Nikoo, M. R., AghaKouchak, A., Dennison, P., and Sadegh, M.: A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes, Science advances, 6, eaaz4571, 2020.

Avanzi, F., Munerol, F., Milelli, M., Gabellani, S., Massari, C., Girotto, M., Cremonese, E., Galvagno, M., Bruno, G., Morra di Cella, U., et al.: Winter snow deficit was a harbinger of summer 2022 socio-hydrologic drought in the Po Basin, Italy, Communications Earth & Environment, 5, 64, 2024.

BAFU: Hydrologisches Jahrbuch der Schweiz 2022, Abfluss, Wasserstand und Wasserqualität der Schweizer Gewässer, Tech. rep., Bundesamt für Umwelt, 2023.

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, Journal of Geophysical Research: Solid Earth, 102, 20 355–20 362, 1997.

Brun, F., Wagnon, P., Berthier, E., Jomelli, V., Maharjan, S., Shrestha, F., and Kraaijenbrink, P.: Heterogeneous influence of glacier morphology on the mass balance variability in High Mountain Asia, Journal of Geophysical Research: Earth Surface, 124, 1331–1345, 2019.

Brunner, M. I.: Reservoir regulation affects droughts and floods at local and regional scales, Environmental Research Letters, 16, 124 016, 2021.

Brunner, M. I., Liechti, K., and Zappa, M.: Extremeness of recent drought events in Switzerland: dependence on variable and return period choice, Natural Hazards and Earth System Sciences, 19, 2311–2323, 2019.

Bruno, G., Avanzi, F., Gabellani, S., Ferraris, L., Cremonese, E., Galvagno, M., and Massari, C.: Disentangling the role of subsurface storage in the propagation of drought through the hydrological cycle, Advances in Water Resources, 169, 104 305, 2022.

Carnahan, E., Amundson, J. M., and Hood, E.: Impact of glacier loss and vegetation succession on annual basin runoff, Hydrology and Earth System Sciences, 23, 1667–1681, 2019.

Chesnokova, A., Baraër, M., Laperrière-Robillard, T., and Huh, K.: Linking mountain glacier retreat and hydrological changes in southwestern Yukon, Water Resources Research, 56, e2019WR025 706, 2020.

Copernicus: European State of the Climate 2022, Tech. rep., Copernicus Climate Change Service, climate.copernicus.eu/ESOTC/2022, 2023.

Cremona, A., Huss, M., Landmann, J. M., Borner, J., and Farinotti, D.: European heat waves 2022: contribution to extreme glacier melt in Switzerland inferred from automated ablation readings, The Cryosphere, 17, 1895–1912, 2023.

De Luca, P. and Donat, M. G.: Projected Changes in Hot, Dry, and Compound Hot-Dry Extremes Over Global Land Regions, Geophysical Research Letters, 50, e2022GL102 493, 2023.

Erfurt, M., Glaser, R., and Blauhut, V.: Changing impacts and societal responses to drought in southwestern Germany since 1800, Regional Environmental Change, 19, 2311–2323, 2019.

Faranda, D., Pascale, S., and Bulut, B.: Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought, Environmental Research Letters, 2023.

Fischer, M., Huss, M., and Hoelzle, M.: Surface elevation and mass changes of all Swiss glaciers 1980–2010, The Cryosphere, 9, 525–540, 2015.

Frans, C., Istanbulluoglu, E., Lettenmaier, D. P., Fountain, A. G., and Riedel, J.: Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960–2099, Water Resources Research, 54, 6202–6225, 2018.

https://doi.org/10.5194/egusphere-2025-404
Preprint. Discussion started: 27 March 2025

Gabbi, J., Huss, M., Bauder, A., Cao, F., and Schwikowski, M.: The impact of Saharan dust and black carbon on albedo and long-term mass balance of an Alpine glacier, The Cryosphere, 9, 1385–1400, 2015.

GLAMOS: Swiss Glacier Mass Balance, release 2024, Tech. rep., Glacier Monitoring Switzerland, https://doi.org/ddoi:10.18750/massbalance.2024.r2024, 2024.

Grab, M., Mattea, E., Bauder, A., Huss, M., Rabenstein, L., Hodel, E., Linsbauer, A., Langhammer, L., Schmid, L., Church, G., et al.: Ice thickness distribution of all Swiss glaciers based on extended ground-penetrating radar data and glaciological modeling, Journal of Glaciology, 67, 1074–1092, 2021.

Gugerli, R., Gabella, M., Huss, M., and Salzmann, N.: Can weather radars be used to estimate snow accumulation on Alpine Glaciers? An evaluation based on glaciological surveys, Journal of Hydrometeorology, 21, 2943–2962, 2020.

Gurtz, J., Baltensweiler, A., and Lang, H.: Spatially distributed hydrotope-based modelling of evapotranspiration and runoff in mountainous basins, Hydrological Processes, 13, 2751–2768, https://doi.org/https://doi.org/10.1002/(SICI)1099-1085(19991215)13:17<2751::AID-HYP897>3.0.CO;2-O, 1999.

Hansel, S., Hoy, A., Brendel, C., Maugeri, M., et al.: Record summers in Europe: Variations in drought and heavy precipitation during 1901–2018, International Journal of Climatology, 42, 6235–6257, 2022.

Höge, M., Kauzlaric, M., Siber, R., Schönenberger, U., Horton, P., Schwanbeck, J., Floriancic, M. G., Viviroli, D., Wilhelm, S., Sikorska-Senoner, A. E., Addor, N., Brunner, M., Pool, S., Zappa, M., and Fenicia, F.: CAMELS-CH: hydro-meteorological time series and landscape attributes for 331 catchments in hydrologic Switzerland, Earth System Science Data, 15, 5755–5784, https://doi.org/10.5194/essd-15-5755-2023, 2023.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., et al.: Accelerated global glacier mass loss in the early twenty-first century, Nature, 592, 726–731, 2021.

Huss, M.: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe, Water Resources Research, 47, 2011.

Huss, M.: Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100, The Cryosphere, 6, 713–727, 2012.

Huss, M.: Density assumptions for converting geodetic glacier volume change to mass change, The Cryosphere, 7, 877–887, 2013.

Huss, M. and Hock, R.: Global-scale hydrological response to future glacier mass loss, Nature Climate Change, 8, 135–140, 2018.

Huss, M., Funk, M., and Ohmura, A.: Strong Alpine glacier melt in the 1940s due to enhanced solar radiation, Geophysical Research Letters, 36, 2009.

Huss, M., Dhulst, L., and Bauder, A.: New long-term mass-balance series for the Swiss Alps, Journal of Glaciology, 61, 551–562, 2015.

Huss, M., Bauder, A., Linsbauer, A., Gabbi, J., Kappenberger, G., Steinegger, U., and Farinotti, D.: More than a century of direct glacier mass-balance observations on Claridenfirn, Switzerland, Journal of Glaciology, 67, 697–713, 2021.

Immerzeel, W., Petersen, L., Ragettli, S., and Pellicciotti, F.: The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas, Water Resources Research, 50, 2212–2226, 2014.

Jost, G., Moore, R., Menounos, B., and Wheate, R.: Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada, Hydrology and Earth System Sciences, 16, 849–860, 2012.

Koboltschnig, G. and Schöner, W.: The relevance of glacier melt in the water cycle of the Alps: the example of Austria, Hydrology and Earth System Sciences, 15, 2039–2048, 2011.

Linsbauer, A., Huss, M., Hodel, E., Bauder, A., Fischer, M., Weidmann, Y., Bärtschi, H., and Schmassmann, E.: The New Swiss Glacier Inventory SGI2016: from a topographical to a glaciological dataset, Frontiers in Earth Science, 9, 704 189, 2021.

Magnusson, J., Gustafsson, D., Hüsler, F., and Jonas, T.: Assimilation of point SWE data into a distributed snow cover model comparing two contrasting methods, Water resources research, 50, 7816–7835, 2014.

Maher, N., Milinski, S., and Ludwig, R.: Large ensemble climate model simulations: introduction, overview, and future prospects for utilising multiple types of large ensemble, Earth System Dynamics, 12, 401–418, 2021.

Maisch, M.: Die Gletscher der Schweizer Alpen: Gletscherhochstand 1850, aktuelle Vergletscherung, Gletscherschwund-Szenarien, Vdf, Hochschulverlag AG an der ETH, 2000.

Mastrotheodoros, T., Pappas, C., Molnar, P., Burlando, P., Manoli, G., Parajka, J., Rigon, R., Szeles, B., Bottazzi, M., Hadjidoukas, P., et al.: More green and less blue water in the Alps during warmer summers, Nature Climate Change, 10, 155–161, 2020.

McCarthy, M., Meier, F., Fatichi, S., Stocker, B. D., Shaw, T. E., Miles, E., Dussaillant, I., and Pellicciotti, F.: Glacier contributions to river discharge during the current Chilean megadrought, Earth's Future, 10, e2022EF002 852, 2022a.

McCarthy, M., Miles, E., Kneib, M., Buri, P., Fugger, S., and Pellicciotti, F.: Supraglacial debris thickness and supply rate in High-Mountain Asia, Communications Earth & Environment, 3, 269, 2022b.

MeteoSwiss: Daily precipitation (final analysis): rhires d, Documentation of MeteoSwiss Grid-Data Products, 2019.

MeteoSwiss: Daily Mean, Minimum and Maximum Temperature: TabsD, TminD, TmaxD, Documentation of MeteoSwiss Grid-Data Products, 2021.

Mishra, V., Thirumalai, K., Singh, D., and Aadhar, S.: Future exacerbation of hot and dry summer monsoon extremes in India, Npj Climate and Atmospheric Science, 3, 10, 2020.

Montanari, A., Nguyen, H., Rubinetti, S., Ceola, S., Galelli, S., Rubino, A., and Zanchettin, D.: Why the 2022 Po River drought is the worst in the past two centuries, Science Advances, 9, eadg8304, 2023.

Mott, R., Winstral, A., Cluzet, B., Helbig, N., Magnusson, J., Mazzotti, G., Quéno, L., Schirmer, M., Webster, C., and Jonas, T.: Operational snow-hydrological modeling for Switzerland, Frontiers in Earth Science, 11, 1228 158, 2023.

Müller, F. B., Caflisch, T., and Müller, G.: Firn und Eis der Schweizer Alpen: Gletscherinventar, (No Title), 1976.

Paul, F.: The new Swiss glacier inventory 2000: application of remote sensing and GIS, Ph.D. thesis, University of Zurich, 2003.

Pritchard, H. D.: Asia's shrinking glaciers protect large populations from drought stress, Nature, 569, 649–654, 2019.

Ragettli, S., Immerzeel, W. W., and Pellicciotti, F.: Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains, Proceedings of the National Academy of Sciences, 113, 9222–9227, 2016.

Rets, E. P., Durmanov, I. N., Kireeva, M. B., Smirnov, A. M., and Popovnin, V. V.: Past 'peak water'in the North Caucasus: deglaciation drives a reduction in glacial runoff impacting summer river runoff and peak discharges, Climatic Change, 163, 2135–2151, 2020.

Réveillet, M., Dumont, M., Gascoin, S., Lafaysse, M., Nabat, P., Ribes, A., Nheili, R., Tuzet, F., Ménégoz, M., Morin, S., et al.: Black carbon and dust alter the response of mountain snow cover under climate change, Nature communications, 13, 5279, 2022.

Rounce, D. R., Hock, R., and Shean, D. E.: Glacier mass change in High Mountain Asia through 2100 using the open-source python glacier evolution model (PyGEM), Frontiers in Earth Science, 7, 331, 2020.

Stahl, K., Weiler, M., Kohn, I., Freudiger, D., Seibert, J., Vis, M., Gerlinger, K., and Bohm, M.: The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change, Synthesis Report I-25, International Commission for the Hydrology of the Rhine Basin, Lelystad, Netherlands, 10, 2016.

https://doi.org/10.5194/egusphere-2025-404
Preprint. Discussion started: 27 March 2025

Tripathy, K. P. and Mishra, A. K.: How Unusual Is the 2022 European Compound Drought and Heatwave Event?, Geophysical Research Letters, 50, e2023GL105 453, https://doi.org/https://doi.org/10.1029/2023GL105453, e2023GL105453 2023GL105453, 2023.

Ultee, L., Coats, S., and Mackay, J.: Glacial runoff buffers droughts through the 21st century, Earth System Dynamics, 13, 935–959, 2022.

Van der Wiel, K., Wanders, N., Selten, F., and Bierkens, M.: Added value of large ensemble simulations for assessing extreme river discharge in a 2 C warmer world, Geophysical Research Letters, 46, 2093–2102, 2019.

Van Lanen, H. A., Wanders, N., Tallaksen, L. M., and Van Loon, A. F.: Hydrological drought across the world: impact of climate and physical catchment structure, Hydrology and Earth System Sciences, 17, 1715–1732, 2013.

Van Lanen, H. A., Laaha, G., Kingston, D. G., Gauster, T., Ionita, M., Vidal, J.-P., Vlnas, R., Tallaksen, L. M., Stahl, K., Hannaford, J., et al.: Hydrology needed to manage droughts: the 2015 European case, Hydrological Processes, 30, 3097–3104, 2016.

Van Loon, A. F.: Hydrological drought explained, Wiley Interdisciplinary Reviews: Water, 2, 359–392, 2015.

Van Loon, A. F. and Laaha, G.: Hydrological drought severity explained by climate and catchment characteristics, Journal of hydrology, 526, 3–14, 2015.

van Tiel, M., Kohn, I., Van Loon, A. F., and Stahl, K.: The compensating effect of glaciers: Characterizing the relation between interannual streamflow variability and glacier cover, Hydrological Processes, 34, 553–568, 2020.

Van Tiel, M., Van Loon, A. F., Seibert, J., and Stahl, K.: Hydrological response to warm and dry weather: do glaciers compensate?, Hydrology and Earth System Sciences, 25, 3245–3265, 2021.

van Tiel, M., Weiler, M., Freudiger, D., Moretti, G., Kohn, I., Gerlinger, K., and Stahl, K.: Melting Alpine Water Towers Aggravate Downstream Low Flows: A Stress-Test Storyline Approach, Earth's Future, 11, e2022EF003 408, 2023.

Vargo, L. J., Anderson, B. M., Dadić, R., Horgan, H. J., Mackintosh, A. N., King, A. D., and Lorrey, A. M.: Anthropogenic warming forces extreme annual glacier mass loss, Nature Climate Change, 10, 856–861, 2020.

Vincent, C., Fischer, A., Mayer, C., Bauder, A., Galos, S. P., Funk, M., Thibert, E., Six, D., Braun, L., and Huss, M.: Common climatic signal from glaciers in the European Alps over the last 50 years, Geophysical Research Letters, 44, 1376–1383, 2017.

Viviroli, D., Zappa, M., Gurtz, J., and Weingartner, R.: An introduction to the hydrological modelling system PREVAH and its pre-and post-processing-tools, Environmental Modelling & Software, 24, 1209–1222, 2009.

Voordendag, A., Prinz, R., Schuster, L., and Kaser, G.: Brief communication: The Glacier Loss Day as indicator for extreme glacier melt in 2022, The Cryosphere Discussions, 2023, 1–7, 2023.

Wang, R., Ding, Y., Shangguan, D., Cuo, L., Zhao, Q., Qin, J., Li, J., and Song, M.: Projections of glacier peak water and its timing in the Sanjiangyuan on the Tibet Plateau, Journal of Hydrology: Regional Studies, 45, 101 313, 2023.

WMO: State of the Global Climate in 2022, Tech. Rep. 1316, World Meteorological Organisation, ISBN 978-92-63-11316-0, 2023.

Zappa, M. and Gurtz, J.: Simulation of soil moisture and evapotranspiration in a soil profile during the 1999 MAP-Riviera Campaign, Hydrology and Earth System Sciences, 7, 903–919, https://doi.org/10.5194/hess-7-903-2003, 2003.

Zappa, M. and Kan, C.: Extreme heat and runoff extremes in the Swiss Alps, Natural Hazards and Earth System Sciences, 7, 375–389, 2007.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., et al.: Historically unprecedented global glacier decline in the early 21st century, Journal of glaciology, 61, 745–762, 2015.

Zeng, N., Qian, H., Roedenbeck, C., and Heimann, M.: Impact of 1998–2002 midlatitude drought and warming on terrestrial ecosystem and the global carbon cycle, Geophysical Research Letters, 32, 2005.