Retreating glaciers and snow cover are amplifying summer droughts in the upper Adige River Basin (Italy)

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Abstract.

Snow and glacier meltwater play a critical role in sustaining summer streamflow in mountains and downstream regions. Yet, understanding glaciers' contributions to buffer river streamflow during droughts remains limited and pose major barriers to improve present and future water management within the context of climate change.

This study evaluates the contribution of glacier melt to summer flows and its mitigation effect of hydrological droughts in the upper Adige River basin, (Italy). We developed and implemented a new dynamic glacier module into the ICHYMOD-TOPMELT hydrological model, annually updating glacier area and improving the quantification of meltwater contributions under progressive glacier retreat (from 111 km2 in 1997 to 79 km2 in 2017).

The hydrological model exhibited robust performances (KGE=0.89 for 1997-2022 for the whole upper Adige River basin at the Bronzolo closing station; 0.88 in summers) capturing observed glacier area, mass balance, and seasonal melt trends. Results show that glacier melt in the upper Adige River basin contributed to an average of 4.5% to total summer streamflow during 1997–2022, with significant spatial variability and reaching 30% in glacierized subbasins. During the severe droughts of 2003, 2005 and 2022, glacier melt contributions ranged

between 4 and 12% at the upper Adige closing section. In 2003, high temperatures and limited Snow Water Equivalent (SWE) led to glacier melt accounting for 11.67% of summer flows. By contrast, the significant runoff deficit in 2005 was driven by colder temperatures, which reduced glacier melt contributions to 4.85%, combined with low SWE conditions. In 2022, the combination of low precipitation, low snow cover and high temperature drove glacier melt. In contrast to the 2003 drought, reduced glacier areas led to lower absolute contributions (8.17%).

Our findings reveal that despite the increased melt rates in recent warm years, retreating glacier areas have reduced their absolute buffering effect. Glacier retreat is weakening the contribution of glaciers to summer flows, increasing the upper Adige River basin's dependence on precipitation and snowmelt, the latter of which is also showing a decreasing trend. For these reasons, accounting for dynamic glacier and snow changes is essential to improve future drought projections and inform adaptive water management in glacier-fed basins within the context of climate and anthropogenic changes.

Keywords: Glacier melt, Adige River basin, droughts, hydrological modelling, climate change**.**

1 Introduction

Recent droughts in Europe caused widespread socio-ecological impacts in the Italian Alps and downstream areas (Avanzi et al., 2026, 2024; Biella et al., 2024; Montanari et al., 2023). The increase in meltwater from snow and glaciers temporarily and partially offset the lack of water from below average snowfall in winter, limited rainfall and exceptionally high temperatures during spring and summer (Leone et al., 2026).

However, rising temperatures and changes in precipitation patterns related to climate change are progressively shrinking and pushing glaciers to a point of no return (Hock et al., 2022; Pepin et al., 2022; Van Tricht et al., 2025). From 2000 to 2023, 39% of the European glacier mass was already lost (The GlaMBIE Team, 2025) and according to the IPCC projections most of the glaciers in the European Alps are expected to disappear by 2100 (Hock et al., 2022). Of particular concerns are the potential consequences of Alpine glacier recession on water provisioning to downstream areas, both on the long term and during drought events, when water is most needed (Ultee et al., 2022).

Yet, understanding glaciers' contributions to buffering river streamflow during droughts remains limited and poses a major barrier to improving present and future water management. On the one hand, this limitation is mainly due to difficulties in dynamically capturing glacier evolution within hydrological models, requiring a trade-off between the limited data availability on glaciers, high model parametrization, and computational costs

(Seibert et al., 2018). In particular, models often rely on either highly parameterized energy-balance equations (Frans et al., 2016; Naz et al., 2014), fully distributed (Maussion et al., 2019) or data-intensive statistical approaches (Shen et al., 2023), which can lead to high computational cost and/or limited interpretability of glacier dynamics and their contributions within hydrological models. Indeed, existing applications have increasingly integrated glacier evolution schemes into hydrological models to simulate mass balance, including equilibrium-line altitude shifts (Linsbauer et al., 2013), volume-area scaling (Luo et al., 2013; Radić and Hock, 2010; Stahl et al., 2008) and the Δh parameterization (Huss et al., 2010, 2008).

On the other hand, existing applications integrating glacier changes into semi-distributed hydrological models (Li et al., 2015; Seibert et al., 2018) often neither consider dynamic glacier evolution nor focus on glacier contributions during droughts. Therefore, there is a need for a simplified, yet reliable glacier dynamic representation in semi-distributed hydrological models to improve the understanding of the hydroclimatic conditions (temperature, precipitation and snow cover anomalies) affecting glacier melt buffering contributions to summer droughts.

The critical 2022 drought situation for the Italian Alps calls for improving our understanding of how much, where and when glaciers contributed to mitigating drought impacts. The upper Adige River Basin in the Italian Alps represents a case in point (Figure 1). Even though it has been considered an area with plenty of water from accumulated snow and glacier melt sustaining summer streamflow and supporting extensive water uses across multiple sectors (Lemus-Canovas et al., 2025; Zebisch et al., 2025), drought events in 2015, 2017 and 2022 challenged water management and have been raising concerns about the high sensitivity of the basin to droughts in the context of ever reducing contributions from snow and glacier melt (Chiogna et al., 2015; Colombo et al., 2023; Stephan et al., 2021).

For these reasons, our research aims to improve long-term predictions of glacier meltwater contributions to streamflow during droughts in the upper Adige River Basin. Moreover, we propose a modelling approach that can be applied to other glacierized catchments to evaluate the effect of glacier melt in mitigating hydrological droughts under conditions of glacier retreat.

To do so, we integrated a novel dynamic glacier module within the existing ICHYMOD-TOPMELT semi-distributed hydrological model (Norbiato et al., 2009, 2008) that annually updates glacier extent using a volume-area scaling relationship to better characterize in space and time glacier melt contributions to streamflow conditions in the upper part of the Adige River Basin (sections 2.2, 3.1 and 3.2). We focused on major drought years including the unprecedented 2022, investigating the role of multiple hydro-climatic conditions (temperature, precipitation and snow cover anomalies) in contributing to droughts (sections 2.5). By doing so, we estimated

glacier contributions during critical conditions hence highlighting potential vulnerabilities associated with future glacier retreat (section 3.3). Finally, we investigated a counterfactual scenario considering the 1997 glacier extent during the 2022 drought to estimate its potential buffering effects during extreme conditions (section 3.3.3).

2 Material and methods

2.1 Study area and input data

The Adige River flows from the eastern Italian Alps to the Adriatic Sea for 410 km, making it the second longest river in Italy with an overall drainage area of 12200 km^2 (Lemus-Canovas et al., 2025; Navarro-Ortega et al., 2015). The upper part of the Adige River Basin (6924 km^2, Figure 1) is characterized by different climatic conditions, with a semi-continental climate in low elevation areas with mild winters and warm summers, and an alpine climate in higher elevations with cold winters and summers (Bertoldi et al., 2023; Tscholl et al., 2025). At higher altitudes, significant water resources accumulate during the winter season in the form of snowfall, which are mobilised during spring. This situation determines the alpine nivo-glacial hydrological regime, characterised by two peaks, one in spring due to snow and glacier melt and the other in autumn due to cyclonic storms (Larsen et al., 2021), which provide abundant water for the development of various and intensive anthropogenic activities. The large availability of water shapes these areas, ranging from reservoirs, hydropower plants and managed pastures at high elevation to irrigated apple orchards and vineyards intensively cultivated at valley bottoms.

Hydrological alterations are mainly induced by various artificial dams with the three largest forming the Lake Resia (116 Mm^3), Lake Vernago (44 Mm^3) and Lake Zoccolo (34 Mm^3) storing water which is mainly used for hydropower production. Most of the lakes receive water from upstream glaciers, the extent of which was mapped to the decreasing values of 111, 98 and 79 km^2 in 1997, 2005 and 2017 (Galos et al., (2022), further annual mass balance data for the whole Adige River Basin are available from Dussaillant et al., (2025)). The study area includes a dense network of hydro-meteorological stations, comprising 88 rain gauges (approximately to 1 per 72 km2), 124 temperature gauges (approximately 1 per 55 km2) and 50 streamflow gauges (1 per 23 km of river), with hourly time series of precipitation, temperature and streamflow, most of them available from the Civil Protection Agency of the province of Bolzano (https://meteo.provincia.bz.it/download-dati.asp).

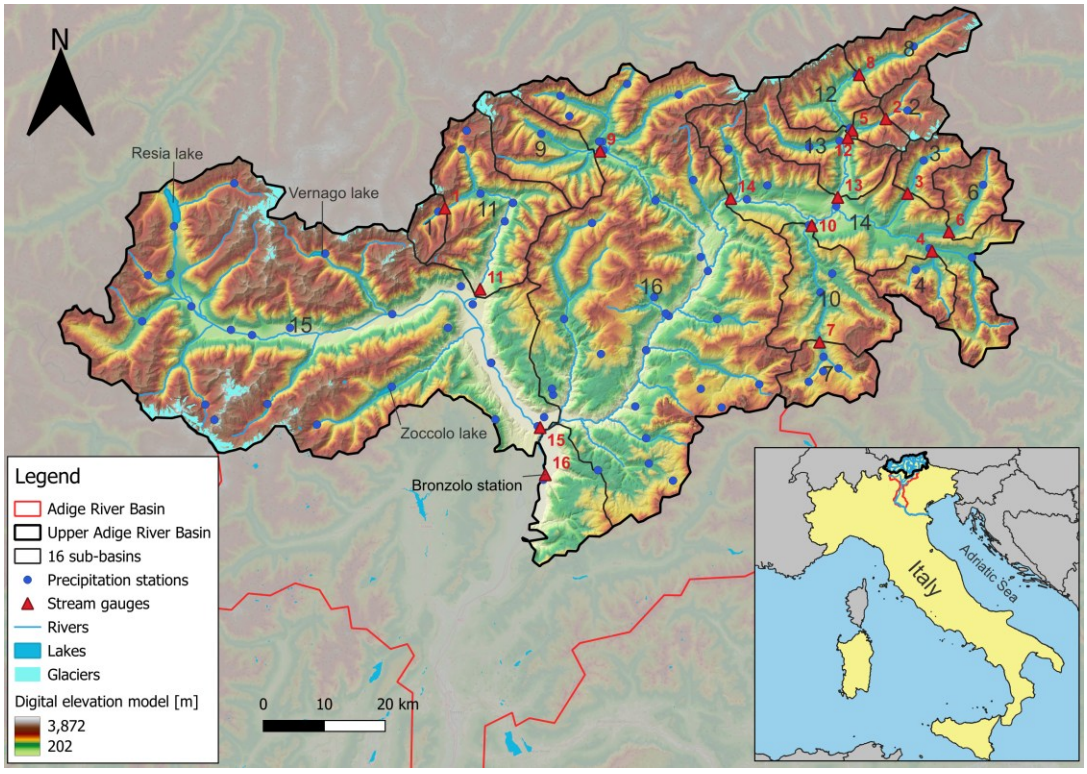


Figure 1 - Map of the upper part of the Adige River Basin (Italy) with glacier extension (Galos et al., 2022) precipitation and river gauge stations, the 16 sub-basins used in the hydrological modelling and the digital elevation model (NASA Shuttle Radar Topography Mission (SRTM) Global. Distributed by OpenTopography, 2013) as a background layer.

2.2 Hydrological model

The simulation of water availability in the upper part of the Adige River Basin starts from the combination of the hydrological model ICHYMOD (Norbiato et al., 2008, Norbiato et al., 2009), with the TOPMELT snow module (Zaramella et al., 2019). The resulting ICHYMOD-TOPMELT is a computationally efficient, semi-distributed conceptual hydrological model that simulates hydro-meteorological state variables (i.e., precipitation, temperature, Snow Water Equivalent (SWE), glacier melt and runoff) at hourly resolution while representing spatial variability in snow and ice melt within subbasins.

The model has been operationally employed by the Province of Bolzano Civil Protection Office for flood forecasting, and previous extensive model validation in the same region has been performed for runoff production (Dalla Torre et al., 2024; Stergiadi et al., 2020), snow and ice melt modelling (Di Marco et al., 2021).

Runoff generation, soil moisture, and evapotranspiration processes are lumped at the sub-catchment scale using the Probability Distributed soil Model (PDM, Moore, (2007, 1985)). Catchment outflows include direct runoff, baseflow, and evapotranspiration (ET), which is estimated using the Hargreaves method and adjusted for soil moisture availability.

In order to properly model snow and ice accumulation and melt processes in complex terrain, the subbasins have been subdivided into elevation and radiation classes, which are updated monthly using clear-sky potential solar radiation. Elevation drives gradients in precipitation and temperature, using regionally calibrated lapse rates. Snow and glacier processes are calculated independently for each combination of elevation and radiation using a modified temperature-index model based on the snowpack formulation of Cazorzi and Dalla Fontana, (1996).

Snow and ice melt are estimated from both radiative and thermal energy exchanges, with separate formulations for daytime, nighttime, and rainy conditions (Zaramella et al., 2019). Snow and ice differ in their reflectivity: snow albedo decreases over time as the surface ages and warms, following Brock et al., (2000), whereas ice maintains a lower, fixed albedo that enhances radiation absorption and accelerates melt. In areas covered by glaciers, glacier ice melt begins when snow water equivalent in a radiation–elevation band falls below a threshold value of 5 mm as defined by (Zaramella et al., 2019). Moreover, we updated the snow-to-ice transformation for each elevation and energy band following a 1:1 volumetric conversion of available SWE to ice depth. Finally, SWE and glacier melt values, based on the elevation and radiation classes for each subbasin, were aggregated to obtain basin-scale values.

2.2.1 The new glacier dynamics module

We developed the simulation of glaciers area dynamics over time and integrated it as a new module into the semi-distributed hydrological model ICHYMOD (Norbiato et al., 2009, 2008). At the foundation of the glacier module is the relationship between glacier volume and area, which was applied at the subbasin level, with the annual hydrological balance used to dynamically update glacier volume.

We used the glacier outline from 1997 and the Digital Elevation Model (DEM) from 1994 to create the initial ice thickness map. This was achieved by applying the flow law described by Glen, (1955) and Farinotti et al., (2009), relying only on glacier surface topography. We divided each glacier into *i* contour lines, where the specific ice flux $\overline{q}_i$ was estimated based on their distance from the equilibrium-line altitude (ELA), following the approach of Huss and Farinotti, (2012). The ice thickness h_i is then calculated as:

$$h_i = \sqrt[n+2]{\frac{\overline{q}_i}{2A}\frac{(n+2)}{(C\rho g \sin\overline{\alpha})^n}}$$

Where A is a flow rate factor calibrated over the whole region ($2.5*10^{-8}$), C is a correction factor for basal sliding, ρ is the ice density, g is the gravitational acceleration, $\overline{\alpha}$ the mean slope in a direction perpendicular to the contour line and n is 3 as standard value adopted in glacier modelling following (Farinotti et al., 2009; Huss and Farinotti, 2012). The ice thickness is then smoothed across contour lines, corrected for local surface slope, distributed using a triangular profile along the contour line, and interpolated across the original grid resolution. The glacier area is reported for each elevation unit and time-invariant radiation classes, assumed representative for the melt period, that form the basis of ICHYMOD-TOPMELT. We validated the results for the initial glacier depth by comparing them with the 1997 South Tyrol glacier inventory, which estimates a total glacier volume of 3326 million m^3 (Galos et al., 2015; Knoll and Kerschner, 2009).

The initial ice thickness is reduced gradually using the Δh methodology developed by Huss et al., (2010):

$$\Delta h = (h_r - 0.3)^2 + 0.6(h_r - 0.3) + 0.09$$

Where Δh is the normalized variation of ice thickness and h_r is the normalized elevation range as in Huss et al., (2010). The parameters used are those recommended for small glaciers, as most of the glaciers have an area below 5 km^2. Using this method, we gradually reduced glacier volume while updating glacier 3D geometry, creating a relationship between glacier volume in each basin and area within each class of time-invariant elevation and radiation. At the end of each hydrological year, we computed the glacier balance for each basin, which is the net balance between the glacier melt and the snow accumulation on the glacier area, assuming that any snow remaining on the glacier at the end of the year directly transforms into ice. We updated the previous-year glacier volume with the glacier balance. For each elevation and energy class, we calculated the new glacier area by linear interpolation between the available steps in the volume-area relationship. Finally, we calculated the glacier volume and area for the whole study basin by summing up all individual subbasins.

2.3 Simulation setup

Following the semi-distributed approach of the ICHYMOD-TOPMELT model, we performed hydrological simulations considering 61 hydrological response units (hereafter referred to as subbasins) within the upper Adige River Basin. For each subbasin, we computed the vertical water mass balance before routing the resulting flows along the river network. From a temporal point of view, we considered the hydrological year from October to September of the following year. In order to effectively start our assessment in October 1997 (year of the first

available glacier area observation), we ran the model at 1-hour time steps from 1996 until 2022, using the first year as a spin-up period and hence discarding it from subsequent analyses.

The parametrization of the hydrological kernel of ICHYMOD-TOPMELT was obtained by maximizing NSE at 16 stream gauges over the period 2003–2019. As simulations of glacier dynamics were highly sensitive to the glacier albedo parameter, we calibrated it through a sensitivity analysis by testing values ranging from 0.4 to 0.8, consistent with those reported in studies conducted in similar areas, e.g., Hartl et al., (2025); Krampe et al., (2022); Richter et al., (2026). We then selected the albedo value that provided the closest match to the available glacier area observations over the entire simulation span (1997-2022).

Finally, an additional simulation considered the same glacier area, as recorded in 1997, for the whole simulation period from 1997 to 2022. By doing so, we aimed to better understand how the drought severity would have been different due to changes in glacier area that occurred over the last 26 years.

2.4 Predictions performance metrics

We considered the Kling-Gupta Efficiency (KGE), as defined by Gupta et al., (2009), to evaluate hydrological model performance over the entire simulation period (1997-2022). To quantify the benefits of shifting from static to dynamic glacier modelling, we considered percentage changes in KGE as well as in the mean bias ratio (MBR) of modelled runoff, both for the entire study period and for the selected summer months of 2003, 2005 and 2022. We evaluated the performance of the glacier module against available observations of glacier area, volume and annual mass balance. In addition, we validated the modelled cumulative mass balance against the annual glacier mass balance dataset of Dussaillant et al., (2025) for the entire study area, covering the period from 1997 onward.

2.5 Hydro-climatic drivers of droughts

For the analysis and characterization of past hydrological droughts occurrence and evolution, we considered a set of hydro-climatic drivers describing the physical conditions that led to droughts. The drivers were implemented and analysed both spatially on the whole upper Adige River Basin and temporally over multiple years and seasons, with a focus on the summer season. In addition, the analysis focused on the 2003, 2005 and 2022 drought years, which were selected as the most severe based on the lowest summer Streamflow Standardized Index (SSI, Modarres, 2007; Telesca et al., 2012), computed for to the July-August-September months (JAS) at the Bronzolo closing section (further information is provided in the Supplementary Material).

The hydro-climatic drivers analysed for past major drought events were precipitation, temperature, SWE at the end of June (assumed to be a proxy for summer snow coverage and therefore for the amount of ice melt

contributing to summer runoff (Penna et al., 2017)), glacier melt and runoff (at the basin outlet). In particular, for each of the 61 subbasins outlets, we computed the area-weighted averages of all the hydro-climatic variables as:

$$Variables_i^{weighted} = \frac{\sum_{k=1}^{i}(Variables_k \times Area_k)}{\sum_{k=1}^{i} Area_k}$$

Where *i* is the given subbasin number while *k* considers all the subbasins nested within subbasin *i*. By doing so, we aggregated the variables and made them comparable according to the runoff routing pathway.

Further, we analysed multiple hydro-climatic drivers (total precipitation, temperature anomalies, and SWE at the end of June) and their z-score values for all modelled years from 1996 to 2023. In particular, the z-score metric (Kreyszig et al., 2011), evaluates how many standard deviations a data point is from the mean of its own dataset, effectively capturing whether values are above or below the climatological mean for each month (positive and negative z-scores, respectively). The z-score provides a standardized interannual comparison of precipitation, temperature, SWE, runoff and glacier melt patterns and captures drought patterns in relation to glacier melt conditions during summer months (i.e., July, August and September).

Finally, we provide spatially distributed representations of summer climatologies as well as focused analyses of the specific droughts in 2003, 2005 and 2022. We reported precipitation, SWE, runoff and glacier melt contributions as percentage differences from the climatological mean, and temperature as an absolute difference.

3 Results

3.1 Glacier module performance

The dynamic glacier module was initialized with the 1997 glacier area observation, iteratively updated and run until 2022 (Figure 2). The calibration of the glacier albedo parameter resulted in a value of 0.65 as it achieved an overall R^2 of 0.84 between the simulated glacier mass balance and the median value in Dussaillant et al., (2025) glacier mass balance observations (bottom panel in Figure 2), while ensuring a close fit to the 2005 and 2017 glacier area observations (top panel in Figure 2). The sensitivity analysis on the albedo range 0.4-0.8 (grey band in Figure 2) shows potential glacier area reduction going from 28% to 49% and mass loss ranging from 15 to 27 m w.e. at the end of the 26-year study period.

The simulated glacier values showed a generalized reduction in both glacier area (-48.93 km^2) and mass (-1.99 km^3) over the 26 years of simulation, corresponding to a mean areal reduction rate of 1.95 km^2/year and mean mass reduction of 0.079 km^3/year, with only a few years showing positive glacier mass accumulation in the basin, such as 2000/2001.

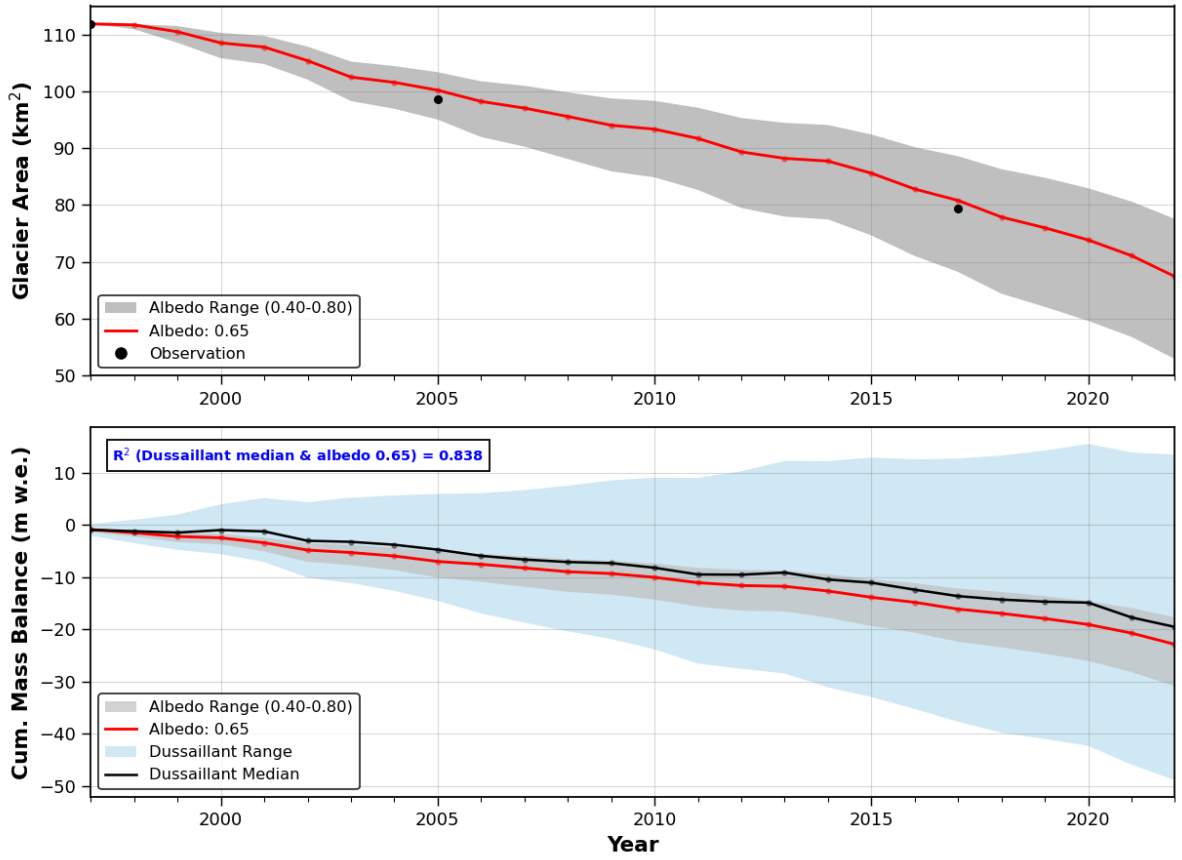


Figure 2 - Time series of glacier area (top panel) and mass balance (bottom panel) from 1997 to 2022 with modelled values (red line) and related uncertainty band (grey area), different albedo values from 0.4 to 0.8 (light blue area), glacier area observations (Galos et al., (2022), black dots) and annual glacier mass changes from Dussaillant et al., (2025, black line).

3.2 Integrated hydrological model results

The hydrological model simulations considered both dynamic and static glacier modules. We compared their results to evaluate glaciers contributions at the subbasins level, over the simulation period and especially during specific drought events. When integrating the dynamic glacier module, the hydrological model showed KGE values ranging from 0.40 to 0.86 for all the glaciated basins, with an average value of 0.70 (Figure 3).

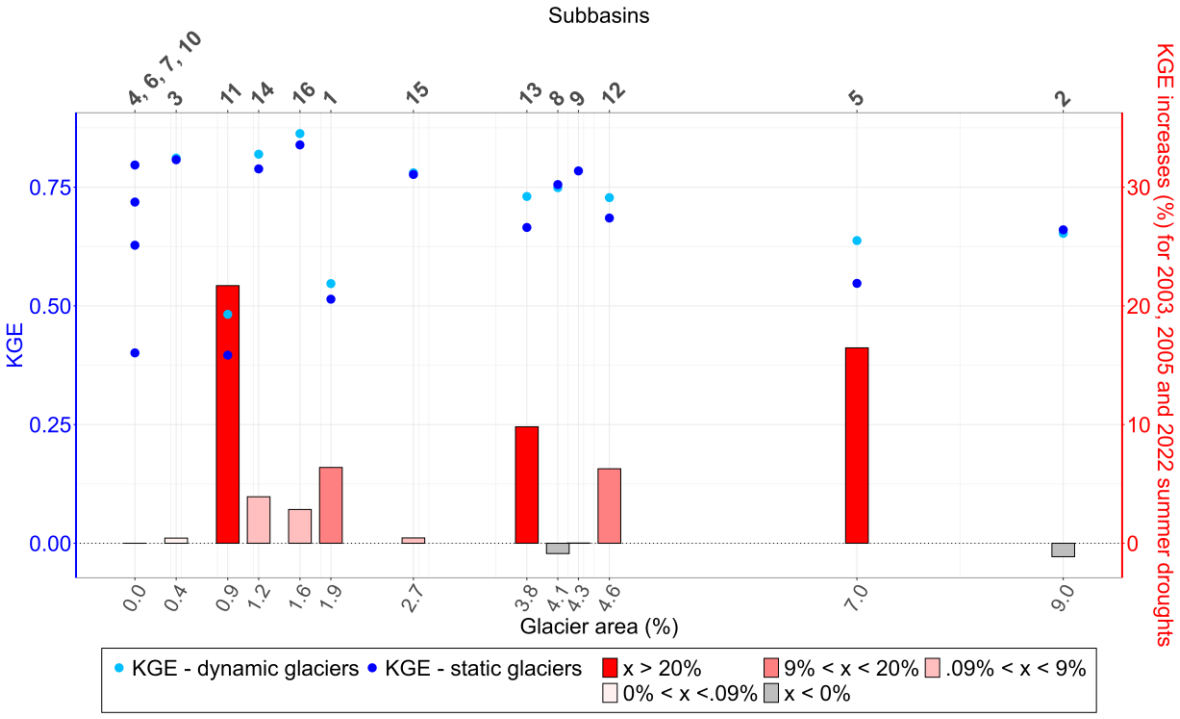


Figure 3 – The Kling-Gupta Efficiency (KGE) performance metric (left y-axis) for the streamflow simulation for the whole period (1998-2022), integrating a dynamic glacier module (light blue dots) and a static glacier module (blue dots) according to increasing values of glacier area over the each subbasin area on the x-axis. The bar plot represents KGE variation (%, right y-axis) between the static and dynamic glacier modelling modules, with specific reference to the summer droughts of 2003, 2005 and 2022 and darker red colour the greater the model improvements.

Over the entire simulation period, the differences between the integration of the dynamic or static glacier modules are limited. For three subbasins, the overall KGE performance has slightly increased, with values below +0.01, while for others it slightly decreased, by less than -0.006. The latter subbasins with declining KGE values for the dynamic module are those showing a negative runoff bias for simulations with the static glacier module (see Tables S3 and S4 in the Supplementary Material). While the dynamic glacier module improved the representation of reduced glacier area conditions, it also implies a decrease in the glacier melt contribution, thereby increasing the already negative runoff bias, ultimately leading to a decrease of the KGE.

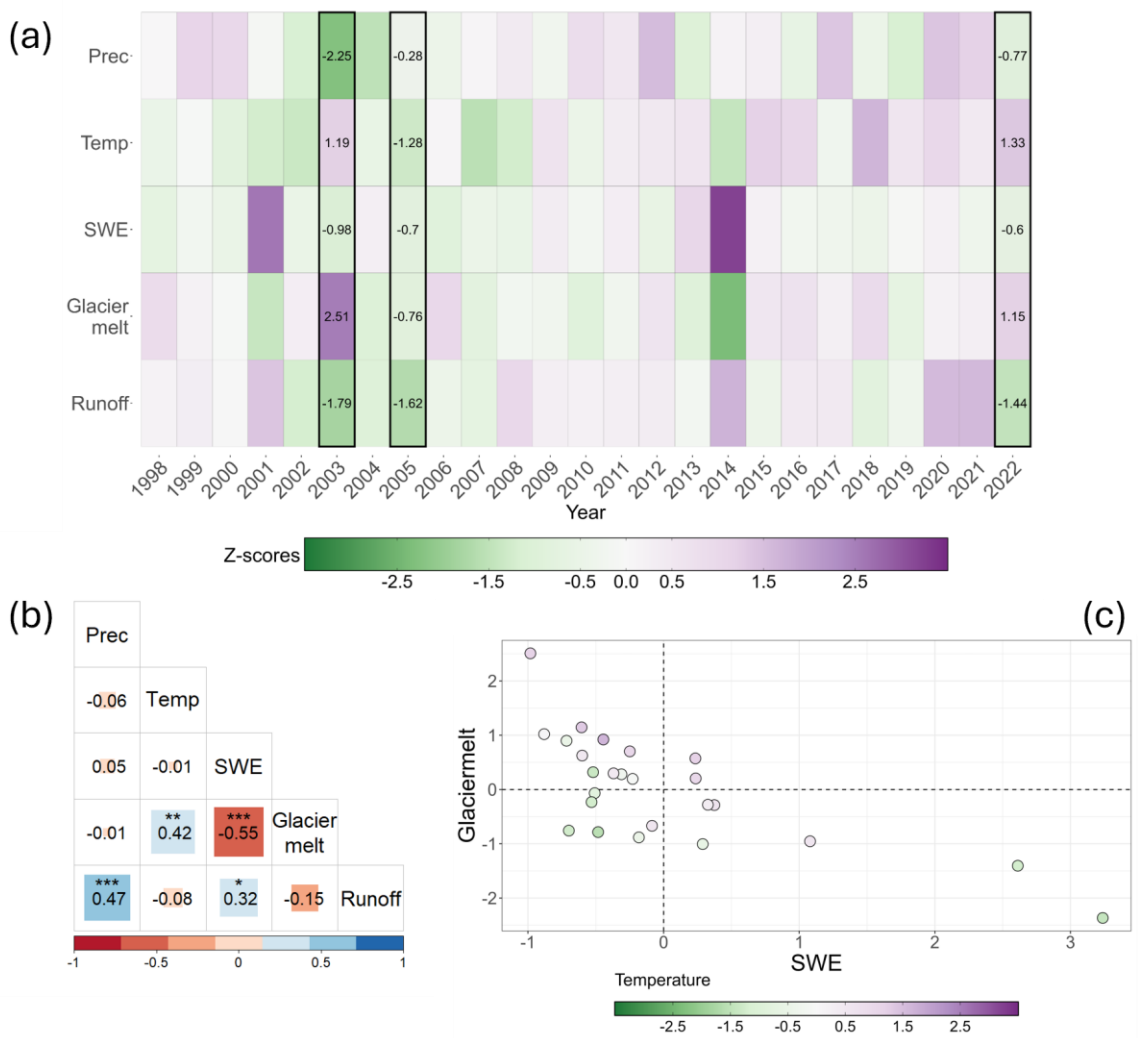
These results become even more pronounced when focusing on the specific summer months (JAS) of drought events in 2003, 2005 and 2022. During that time, streamflow reached its lowest observed levels over the simulated period, hence making the glacial meltwater contribution proportionally more relevant. During the three considered droughts, the simulations with the dynamic glacier module showed improved KGE performance for all glacierized

subbasins, except for two, as depicted in the bar plot of Figure 3. In particular, the largest increases were observed in subbasin n.11 (Passirio, +21.7%), n.5 (Rio Riva a Caminata, +16.5%) and n.13 (Aurino a S.Giorgio, +9.8%), while a slight KGE decrease was recorded for the subbasins n.8 (Aurino a Cadipietra, -0.87%) and n.2 (Rio Riva a Seghe, -1.14%). This latter subbasin shows the lowest percentage KGE decrease, despite having the highest proportion of glacier coverage. In particular, the KGE value slightly decreases from 0.66 to 0.65 due to a decrease in MBR from 0.78 to 0.77 when shifting from the static to the dynamic glacier module.

3.3 Evaluating the hydro-climatic drivers of droughts

3.3.1 Temporal patterns of hydro-climatic variables in the upper Adige

Results from the simulations were aggregated at the basin scale to support the temporal analysis of hydro-climatic variables driving droughts. The purpose was to understand the hydroclimatic conditions that lead to the maximum glacier compensation effect during droughts. Figure 4 (panel a) shows a heatmap of interannual z-score values over summer seasons (JAS) from 1998 to 2022 for all hydro-climatic variables (with the exception of SWE, for which the z-score was evaluated based on its value at the end of June) together with their related mutual correlation values (panel b). In the heatmap, no single hydro-climatic variable can fully capture drought conditions, as high SWE can compensate for below-average summer precipitation (e.g., years 2001 and 2014), while winters with below-average snow can be compensated for by a rainy summer (e.g., years 2012 and 2017). Nevertheless, an overview on the correlation analysis between the hydro-climatic variables provides further insights.



285 **Figure 4 - Heatmap of the z-score values (green negative, purple positive) for the 5 hydro-climatic drivers of droughts for the whole upper Adige River Basin from 1998 to 2022 calculated for the summers months JJA and at end of June for SWE (panel a). Mann–Kendall correlations (from −1 to 1) between variables and significance: ∗, ∗∗ and ∗∗∗ refer to significant p-values ≤ 0.05, ≤ 0.01 and ≤ 0.001, respectively (panel b). Scatterplot of z-scores for SWE and glacier melt with colours for the temperature z-scores (panel c).**

290 In particular, runoff shows a moderate positive correlation with precipitation (r=0.47, p<0.001) with decreasing correlation values with SWE (r=0.32, p<0.05), while it appears uncorrelated with glacier melt (p>0.05, Figure 4, panel b). On the one hand, SWE and glacier melt show a moderate and highly significant negative correlation (r=-0.55, p<0.001), recalling the blanketing effect of abundant snow cover, which protect glacier from melting. On

the other hand, glacier melt is driven by summer temperature ($r=0.42$, $p<0.01$) as it is highlighted by the conditions in 2003 and 2022 conditions, when high temperature combined with low SWE led to above-average glacier melt during severe hydrological droughts.

We further examined the apparent relationship between SWE, temperature, and glacier melt visualizing each summer in a scatterplot (Figure 4, panel c). High glaciers melt rates typically occur under above-average temperatures and below-average SWE at the end of June, confirming the behaviour suggested by the correlation analysis.

3.3.2 Focus on the major past hydrological droughts

In the selected years of 2003, 2005 and 2022, different temporal and spatial dynamics led to runoff deficit and droughts across the study area (Figure 4 and Figure 5). The year 2003 was characterized by exceptionally hot and dry spring and summer conditions triggering a hydrological drought. In particular, *Val d'Ultimo* showed a reduction of 60% compared to its average summer (JAS) runoff of 75 mm and *Val Sarentino* showed a 58% reduction relative to its runoff average of 68 mm (Figure 5, further information on subbasins locations and names are available in Figure S1 and Table S2 of the Supplementary Material). Other areas in the north-east also showed runoff reductions of around 50% relative to an average runoff of 99 mm, despite increased glacier melt contributions. The runoff decline was primarily driven by strong precipitation deficits that affected the entire study area. The most severe deficit was observed in *Val d'Ultimo*, with a summer precipitation reduction of 77% below the average value of 106 mm. Temperature anomalies were above average, with a mean increase of 0.89 °C across the upper Adige River Basin. Snow Water Equivalent (SWE) at the end of June showed negative anomalies throughout the region, with 14 subbasins recording values 100% below their climatological mean. The 14 subbasins that showed the lowest decrease in SWE during summer 2003 were also those that showed the lowest climatological SWE values over the 26-year simulation period. Due to the hot summer conditions in 2003, glacier melt strongly contributed across the region. Glacierized subbasins in the southwest showed values 101% higher melt compared to the summer average values of 0.7–1.2 mm, while northeastern glaciers showed even stronger increases reaching 180% above the average value of 0.7 mm.

In 2005, the runoff deficits across the region were the result of different factors compared to the 2003 drought. The most pronounced runoff reductions occurred in the already dry western areas, with runoff deficits of 55% relative to the average runoff of 107 mm in *Val di Solda* and 54% relative to the average runoff of 81 mm in the lower *Val di Solda*.

In contrast, the eastern part of the region, where both precipitation and glacier melt anomalies were mild or even positive, experienced more limited runoff deficits of around 20%. These patterns were influenced by a less severe precipitation deficit than in 2003. The western part of the region consistently experienced dry conditions, with precipitation deficits down to -40%, while the southern part recorded positive anomalies of up to 22% and the eastern part up to 18%.

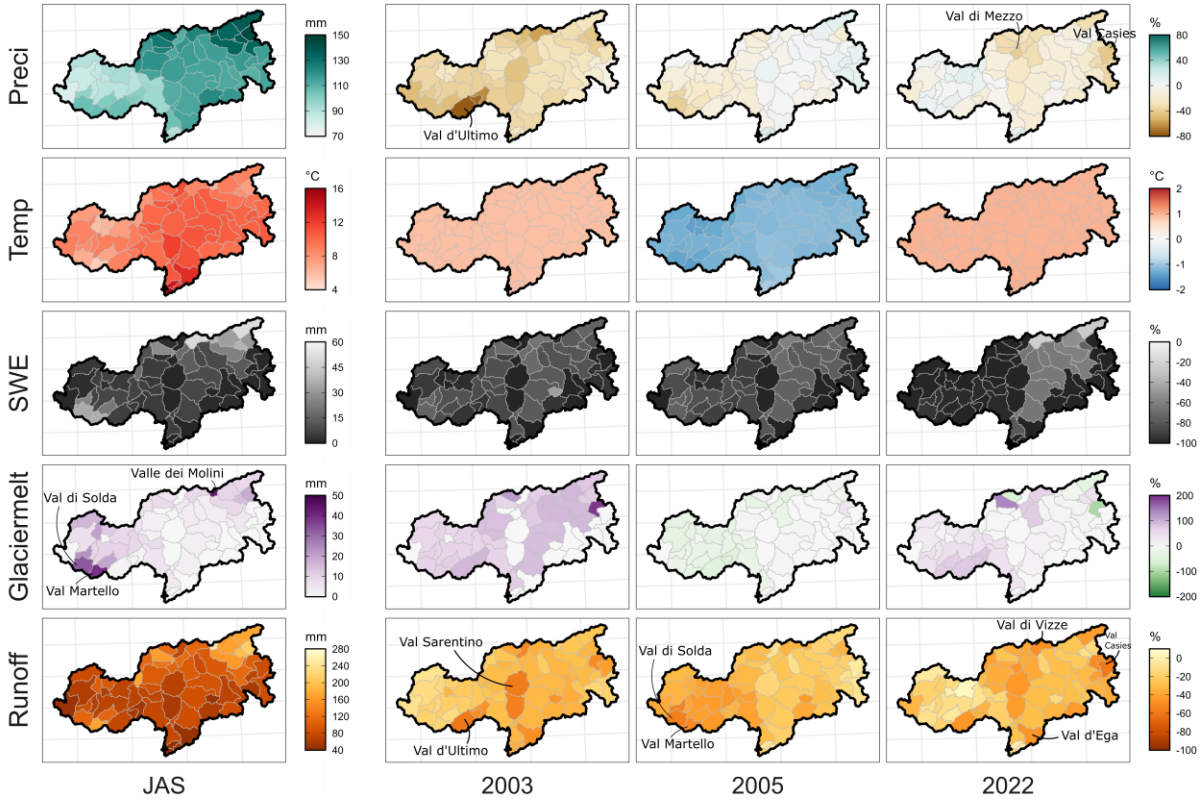


Figure 5 – Spatial representation of climatological mean (first column on the left) and anomalies (three columns on the right) computed for the average summer values from 1997-2023 within the upper Adige River Basin of the hydro-climatic variables. Only SWE consider values at the end of June. The anomalies refer to the selected drought years of 2003, 2005 and 2022.

Temperature anomalies were negative across the entire area, with a widespread cooling of 0.8-1.4 °C below average. This colder-than-average summer had a notable impact on other hydrological components. Despite the cold summer temperatures, SWE at the end of June was similar to that of 2003, with deficits ranging from -100% to -60% across the region, particularly in headwater subbasins. Differently than in 2003, glacier melt in 2005

showed lower values, largely driven by the cooler temperatures. However, some eastern subbasins still exhibited glacier melt anomalies up to 31%, contributing to the relatively smaller runoff deficits in that part of the region.

During the severe 2022 drought, precipitation anomalies, especially in the eastern part, compounded with higher-than-average temperature (+1 °C) and one of the most severe SWE deficits, especially for the western part. Runoff deficits reached -60% relative to the average summer runoff of 81 mm in *Val Casies*, 48% relative to 111 mm in *Val di Vizze*, 47% relative to 48 mm in *Val d'Ega* and 46% relative to the average summer runoff of 75 mm in *Val d'Ultimo*. Precipitation deficits were mostly located in the centre-eastern part. *Val Casies* and *Val di Mezzo* recorded the lowest values with deficits of 45% and 42% respectively, relative to summer averages of 121 mm and 113 mm. Positive temperature anomalies were widespread across the region, with average values of +1 °C, contributing to accelerated snow- and ice-melt processes. SWE at the end of June showed one of the most severe reductions, particularly in the western part. Overall, 75% of the subbasins showed SWE deficits below 90%, except for the north- and central-eastern areas. Glacier melt was only partially affected by the warmer conditions and reduced snow cover. Increased glacier melt was observed in some areas, such as in *Val Ridanna*, which recorded 156% increase relative to its summer average of 7.1 mm. However, in other subbasins, glacier melt was negative, including reduction of 100% in *Val di Anterselva*, 62% in *Val di Fleres*, and 41% in *Val Aurina*.

3.3.3 What if glaciers did not retreat?

To further quantify the effects of glacier retreat on droughts in the upper Adige, we compared runoff and glacier melt conditions from 1997 to 2023 considering a counterfactual scenario of constant glacier area and volume as it was in 1997. Results show progressively increasing differences both in terms of glacier melt and runoff during the selected drought events. This condition highlights the growing influence of glacier recession and the buffering capacity lost that would have been available during drought years. During the 2003 drought, average summer glacier melt from the dynamic simulation was 7.81% lower than under 1997 glacier conditions, indicating a relatively limited loss of buffering capacity. The difference increases to 15% in 2005 and reached 44.7% in 2022, demonstrating the growing impact of glacier retreat on meltwater availability during dry summers (**Figure *6***).

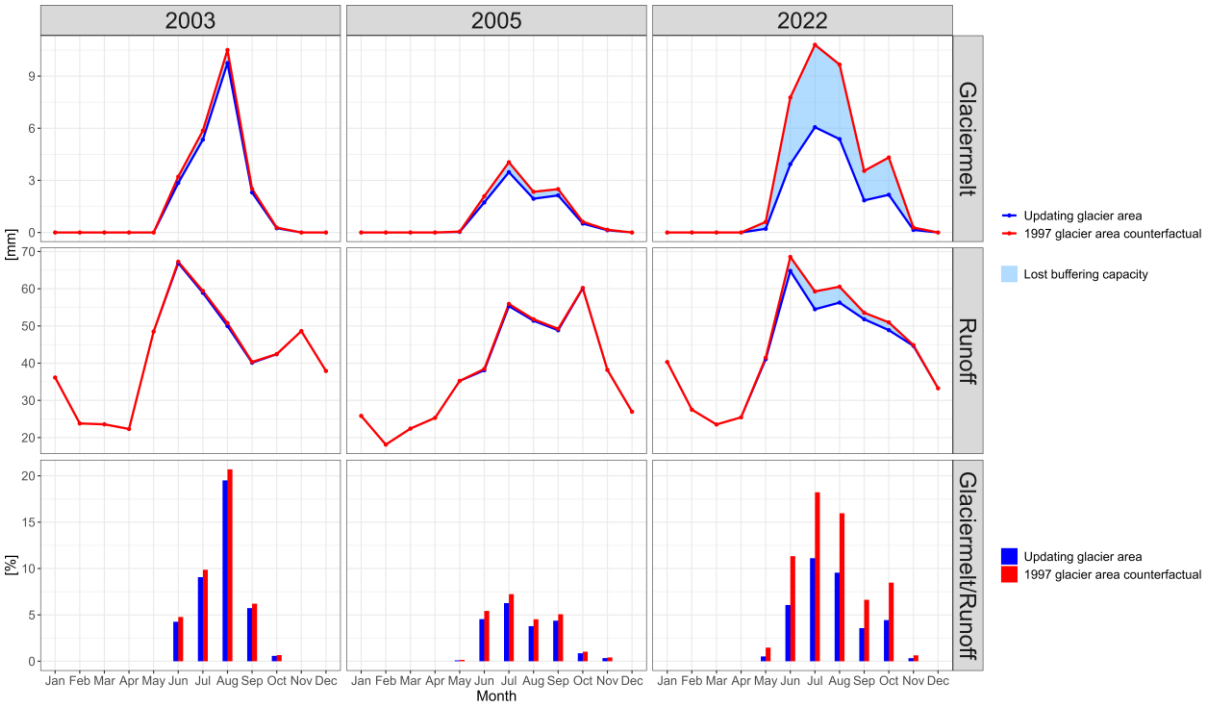


Figure 6 – Simulating the lost buffering capacity (light blue shaded area) in terms of glaciermelt, runoff and glaciermelt contribution to runoff at the Bronzolo gauge station considering the 1997 glacier areas (red lines/bar) and yearly updating the glacier area (blue lines/bar).

The loss of glacier buffering capacity translated into reductions in summer runoff, although the magnitude of the effect was smaller than that observed for glacier melt. In 2003, runoff was 0.99% lower in the dynamic simulation, while in 2005, both scenarios produced similar runoff values mainly due to lower contributions from glaciers during the cold 2005 drought conditions. In 2022, runoff was 6.23% lower than in the counterfactual scenario.

The percentage contribution of glacier melt to total runoff most clearly shows the erosion of glacier buffering capacity. In relation to the 1997-glacier counterfactual, the contribution of glacier melt to total runoff was reduced by 6.89% during the 2003 drought, 14.29% in 2005 and 41.01% in 2022. This result indicates that by 2022, more than two-fifth of the potential glacier buffering capacity that would have been available under the 1997 glacier extension had already been lost. While the reduction in glacier melt is mainly attributable to shrinking glacier area, the longer the simulation period and the wider the gap between the two simulations from 2003 to 2022 dynamic and 1997-glacier scenario, highlighting the reducing capacity of the upper Adige river basin to sustain streamflow during dry and warm summers.

4 Discussions

This study highlights the evolving role of glaciers in buffering hydrological responses to drought in the upper Adige River Basin. During major past droughts, glacier melt contributed between 4% and 13% of summer runoff. However, this buffering capacity is diminishing due to ongoing glacier retreat. Over the 26 years of simulation, glaciers in the upper Adige River Basin shrunk at an average rate of 1.95 km² per year (Figure 2), significantly reducing their ability to sustain summer flows during dry periods.

At the single summer drought event, glacier melt contributions is shaped by the interaction among cryospheric and climatic conditions (Figure 4 and Figure 5). In particular, the amount of snow cover at the end of June and the high temperature conditions during July-August-September months play a critical role in determining summer glacier melt within the upper Adige River Basin (Figure 4). Reduced snow cover shortens the duration of snow melt contribution while also exposing glacier ice to high temperatures earlier in the summer and hence increasing glacier melt rates. This result aligns with previous studies on factors driving glacier compensation effects in other glacierized areas in the world (Jenicek et al., 2016; Van Tiel et al., 2021).

The comparison of the 2003, 2005, and 2022 major drought events also provides evidence that the buffering role of glaciers is changing over time. Although 2022 experienced temperature conditions comparable to those of 2003, the compensatory effect provided by glaciers declined from 12% of summer runoff in 2003 to 8% in 2022. While the inherent uncertainty embedded in multiple factors such as glacier extent, elevation range, aspect, glacier melt data and model uncertainties, the implemented glacier dynamic module consistently indicates a lower glacier melt contribution in summer 2022 than in 2003. This result points to the reduction in glacierized area as an important factor limiting meltwater availability during recent droughts.

The exceptional importance of glacier melt during the 2022 drought has also been identified in other glacierized catchments in northern Italy, although the magnitude of the estimated anomaly differs among regions. In the upper Adige River basin, results indicate that 2022 summer glacier melt contribution was 280% above the climatological mean, whereas Leone et al., (2026) found an anomaly of about 350% for other glacierized catchments in Valle d'Aosta and Valtellina in northern Italy. Despite these quantitative differences, both studies indicate that enhanced glacier melt substantially sustained summer streamflow during the 2022 drought.

The declining glacier melt contribution to summer streamflow (Figure 5 and Figure 6) between the two similar droughts of 2003 and 2022, suggests that the glacier peak water in the upper Adige River basin may already have been reached or is being approached. Similar patterns have been reported across the Alps, where glacier melt remains an important component of summer streamflow during dry years, even though its absolute contribution is already declining because of glacier retreats (Huss and Hock, 2018; Sommer et al., 2020; van Tiel et al., 2026).

For these reasons, the continued loss of this natural water storage could have important implications for water-demanding sectors in the future, particularly hydropower generation and irrigated agriculture, whose demands can remain high during periods of limited summer availability (Clason et al., 2022; Schaefli et al., 2019). Moreover, sharp declines during drought periods could strengthen upstream-downstream dependencies and increase the potential for competition among water uses. These pressures are likely to become more relevant under future climate and socio-economic changes. Future water management plans should therefore consider the progressive loss of cryospheric buffering and combine short-term improvements in water allocation with longer-term adaptation and transformation strategies addressing water demand, sectoral priorities and basin-wide coordination.

4.1 Limitations

While the integration of the glacier module into the ICHYMOD-TOPMELT hydrological model has provided valuable insights into glacier melt contributions and drought responses in the upper Adige River Basin, some limitations calling for future improvements must be acknowledged.

The glacier module is based on the empirical relationship between glacier volume and area at the catchment scale. Although it performs well in simulating overall glacier melt contributions, it cannot capture the full complexity of glacier dynamics, such as internal flows, at the individual glacier level. Moreover, the module assumes that available SWE over glacier surfaces at the end of each hydrological year, directly contributes to glacier mass balance. This approach shows limitations to accurately simulate specific years with net glacier mass gain, as observed in certain periods. Additionally, while the model reproduces glacier area evolution reliably, its representation of mass balance is constrained by uncertainties in the Dussaillant dataset used for calibration (Figure 2). Nonetheless, the cumulative mass balance estimates from the model fall within the uncertainty range of Dussaillant-derived values, supporting its value for basin-scale assessments.

The use of a fixed albedo value in the glacier model constitutes a model simplification compared to state-of the art glaciers models (Maussion et al., 2019). Although glacier albedo may vary spatially and temporally, we tested a range of spatio-temporally fixed parameters in order to (i) substantially reduce the computational effort and (ii) avoid a clear risk of equifinality, given the limited validation data available relative to the large number of potential spatio-temporal albedo configurations. Several other parameters equally influence glacier melt dynamics, namely combined melt factor for combined radiation-temperature driven melt, rain melt factor and night melt factor, all handling ice melt in different conditions. However, these parameters are coupled for snow and ice melt by model design, and therefore simultaneously affecting the behaviour of both storages. We consequently focused the calibration on glacier albedo, which is the only parameter in the model framework that allows glacier melt to be

adjusted independently of snowmelt. The selected calibration value of 0.65 is higher than usual values typically associated with bare glacier ice and is closer to those reported for firn. Nevertheless, it lies within the range reported by studies conducted in comparable Alpine environments (e.g., Hartl et al., 2025; Krampe et al., 2022; Richter et al., 2026) and remains below the fresh snow albedo value of 0.9 used in the model.

The performance of the integrated hydrological model shows a decreasing trend in Kling-Gupta Efficiency (KGE) values for subbasins with glacier coverage exceeding 1%. These subbasins are typically small, high-elevation catchments where modelling challenges are amplified due to limited data availability, meteorological forcings uncertainty and the complexity of snow- and ice-related processes. In this regard, only eight glacierized subbasins had complete runoff observations for the summer periods of 2003, 2005, and 2022, restricting the robustness of model validation and of the analyses focused on these years, as detailed in the Supplementary Material.

Despite these limitations, including a dynamic glacier module improved streamflow representation during low-flow summer events. The improved model enhanced the glacier melt quantification during droughts and provided a valuable tool for understanding the conditions that lead to high or low glacier melt contributions to summer drought, that can be applied to other mountain glacierized catchments. The tool can be used for adapting water resources management in alpine regions within climate change context, where glacier retreat is altering seasonal water availability.

5 Conclusions

This study provides a modelling approach to quantify the role of glaciers and snow cover in buffering summer droughts, implementing a novel dynamic glacier module into the ICHYMOD-TOPMELT hydrological model. The application in the upper Adige River Basin shows an almost monotone trend of glacier retreat for consecutive 26 years. Focusing on the 2003, 2005 and 2022 most severe droughts, we show how the combination of multiple hydroclimatic variables (i.e., summer precipitation, temperature and especially snow water equivalent at the beginning of summers) drives the amount of glacier melt that mitigate hydrological droughts. Glacier melt contributions ranged between 4 and 12% at the upper Adige closing section while the glacier extension decreases (from 111 km2 in 1997 to 79 km2 in 2017) is leading to a significant decline in glacier melt contribution to the overall runoff, especially during acute hot and dry events. This condition suggests that the glacier peak water in the upper Adige River basin may already have been reached or is being approached. Moreover, our counterfactual analysis showed that, if glaciers had retained their 1997 extent, their contribution to total runoff during the 2022 drought could have been 41.01% higher than the contribution estimated under the actual 2022 glacier extent. For these reasons, the continued glacier loss and its implications on water management need to be considered in future

plans, particularly with increasing demand across multiple sectors and for downstream users. Given the increasing emissions and global temperature and consequent glaciers disappearance (Van Tricht et al., 2025), our results call for proactive adaptation and transformation strategies within water demand planning accounting for the decreasing buffering glaciers role to sustain summer flows and mitigate drought conditions.

Data and code availability

Data and code are available by request to the Authors.

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Conflict of interest/Competing interests

The authors declare no conflict of interest.

Author contribution

SS, ST and GB conceived the study, and SS performed the analysis with the significant support from ST, GB, AG, MZ, DZ. SS and ST wrote the first manuscript draft with support from AG, DZ and GB. MB, RD, MP contributed with insights, discussed the argument and review the manuscript. ST secured funding. SS and ST equally contributed to the study.

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