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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; 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 drought of 2003, 2005 and 2022, glacier melt contributions ranged between 4 and 12% at the upper Adige closing section. In 2003, high

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temperatures and limited SWE led to glacier melt accounting for 11.67% of summer flows. By contrast, colder temperatures in 2005 reduced contributions to 4.85% compounding with low SWE conditions and leading to a significative runoff deficit. In 2022, the combination of low precipitation, low snow cover and high temperature drove glacier melt. Differently than 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 their contribution to summer flows, increasing the upper Adige River basin's dependence on precipitation and snowmelt, 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, water scarcity.

1 Introduction

The unprecedented 2022 drought in Europe was one of the worst event ever recorded for large parts of Europe with severe socio-ecological impacts in the Italian Alps and related downstream areas (Avanzi et al., 2024; Biella et al., 2024; Montanari et al., 2023).

The combination of below-average snowfall in winter, limited rainfall and exceptionally high temperature during spring and summer led to widespread drought impacts across multiple sectors (Avanzi et al., 2025, 2024). In those areas where glaciers are still present, the increase in meltwater temporarily and partially offset some of the summer drought impacts (Leone et al., 2025).

However, temperature increase and variation of precipitation patterns related to climate change are progressively shrinking glaciers and pushing them 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 glaciers 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 glaciers recessions 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 the glaciers' contributions to buffer river streamflow during droughts remains limited and pose major barriers to improve present and future water management. On the one hand, this limitation is mainly due to

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difficulties to dynamically capture glacier evolutions within hydrological models finding a trade-off among the limited data availability on glaciers, high models parametrization, and computational costs (Seibert et al., 2018). In particular, models often rely on either highly parametrized 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 costly and/or difficult interpretability on glacier dynamics and their contributions in hydrological models. Indeed, existing applications have increasingly integrated glaciers 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 glaciers changes into semi-distributed hydrological models (Li et al., 2015; Seibert et al., 2018) often do not consider dynamic glacier evolution and contributions during droughts. Therefore, there is the need for a simplified, yet reliable glacier dynamic representation in semi-distributed hydrological models to improve the understanding of the hydro climatic 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 on how much, where and when glaciers contributed to mitigate drought impacts. The upper Adige River Basin represents a case in point. Even though it has been considered an area with plenty of available water coming from accumulated snow and glacier melt sustaining summer streamflow and the high water uses from 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 on 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 mitigating hydrological droughts under retreating glaciers conditions.

To do so, we integrated a 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 contribution 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) contributing to droughts (sections 2.5). By doing so, we estimated glacier contribution

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during critical conditions hence highlighting potential cases of vulnerabilities to future glacier retreats (section 3.3). Finally, we investigated a counterfactual scenario considering the 1997 glacier extension during the 2022 drought to estimate their 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 Resia lake (116 Mm^3), Vernago lake (44 Mm^3) and Zoccolo lake (34 Mm^3) storing water which is mainly used for hydropower production. Most of the lakes receive water from upstream glaciers, the extension of which was mapped to the decreasing values of 111, 98 and 79 km^2 during 1997, 2005 and 2017 (Galos et al., (2022), further data on annual mass balance for the whole Adige River Basin available from Dussaillant et al., (2025)). The study area includes a dense network of hydro-meteorological stations, comprising 88 rain gauges (equivalent to 1 per 72 km2), 124 temperature gauges (1 per 55 km2) and 50 streamflow gauges, with hourly time series of precipitation, temperature and streamflow available from the Civil Protection Agency of the province of Bolzano.

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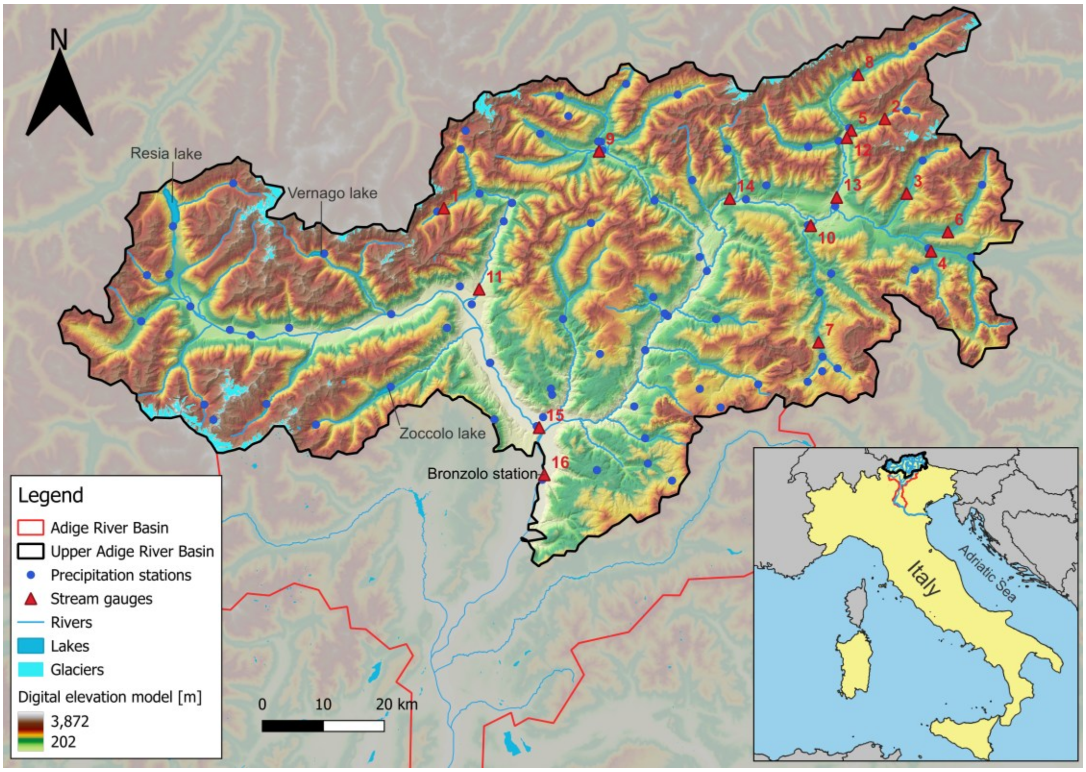

115 **Figure 1 - Map of the upper part of the Adige River Basin (Italy) with glacier extension (Galos et al., 2022) precipitation and river gauge stations as well as the digital elevation model (NASA Shuttle Radar Topography Mission (SRTM) Global. Distributed by OpenTopography, 2013) as a background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

2.2 Hydrological model

The simulation of water available in the upper part of the Adige River Basin starts from the combination of the
120 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-meteorologic state variables (i.e., precipitation, temperature, SWE, glacier melt and runoff) at hourly resolution while representing spatial variability in snow and ice melt within subbasins.

125 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).

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Runoff generation, soil moisture, and evapotranspiration processes are lumped at the sub-catchment scale using the Probability Distributed soil Model (PDM - Moore, 2007, Moore, 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, we divided the subbasins by elevation and radiation classes, which are updated monthly using clear-sky potential solar radiation. Elevation drives a gradient in precipitation and temperature, using regionally calibrated lapse rates. We calculated snow and glacier processes independently on 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 higher, fixed albedo that enhances 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. 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 have an overall value.

2.2.1 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 the glacier volume.

We used the glacier outline of 1997 and the Digital Elevation Model (DEM) from 1994 to create the initial ice thickness map. This is done 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 $\overline{q}_i$ is 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:

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

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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. 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. The glacier area is reported for each unit of elevation and time-invariant radiation classes, assumed representative for the melt period, that are at the base of ICHYMOD-TOPMELT. We validated the results on 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 glaciers' volume while updating their 3D geometry, creating a relationship between glacier volume on each basin and area on each class of time-invariant elevation and radiation. At the end of each hydrological year, we computed the glacial balance for each basin, which is the net balance between the glacier melt and the snow accumulated over 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 glacial balance. For each unit of elevation and energy, we calculated the new glacier area by linear interpolation between the available steps in the volume-area relation. Finally, we calculated the glacier volume and area for the whole study basin summing up all individual subbasins.

2.3 Simulation setup

Following the semi-distributed approach of the ICHYMOD-TOPMELT model, we performed hydrological simulations considering 65 hydrological response units (hereafter referred 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 run the model at 1h timesteps 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 maximizing NSE at 16 stream gauges over 2003–2019. As the simulation of glacier dynamics was highly sensitive to the glacier albedo

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parameter, we calibrated it through a sensitivity analysis (testing the range 0.4-0.8), assessing what value ensured the closest match to available glacier area observation over the entire simulation span (1997-2022).

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

2.4 Predictions performance metrics

We considered the Kling-Gupta Efficiency (KGE), as defined by Gupta et al., (2009), for evaluating the hydrological model performance over the entire simulation period 1997-2022. To quantify the benefits of shifting from static to dynamic glacier modelling, we considered percent changes in KGE as well as in the mean bias ratio (MBR) of modelled runoff, for both the whole period and for selected summer months of 2003, 2005 and 2022. We evaluated glacier module performance 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 onwards.

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 2003, 2005 and 2022 most severe drought years selected based on the lowest summer Streamflow Standardized Index (SSI, Modarres, 2007; Telesca et al., 2012), computed with reference to July-August-September months (JAS) at the Bronzolo closing section (further information 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 the snow budget resulting from winter-spring prior to the melting season), glacier melt and runoff (at the basin outlet). In particular, for each of the outlet of the 65 subbasins, 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 and made all variables comparable according to the runoff routing pathway.

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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 the 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 if their values are above or below the climatological mean for each month (positive and negative z-scores, respectively). Z-score provides a standardized interannual comparison of precipitation, temperature, SWE, runoff and glacier melt patterns and capture 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 focuses on specific droughts in 2003, 2005 and 2022. We reported precipitation, SWE, runoff and glacier melt contribution as percentage differences from the climatological mean, and temperature as absolute differences.

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 glacier albedo parameter was calibrated to best fit the available glacier area observations for 2005 and 2017. The resulting value of 0.65 achieved an overall R^2 equal to 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). Figure 2 also shows the uncertainty band for the 0.4-0.8 albedo values highlighting how albedo is a key calibration parameter of the model, The simulated glacier values showed a generalized reduction of 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, except a few cases of positive glacier mass accumulation in the basin such in 2000/2001.

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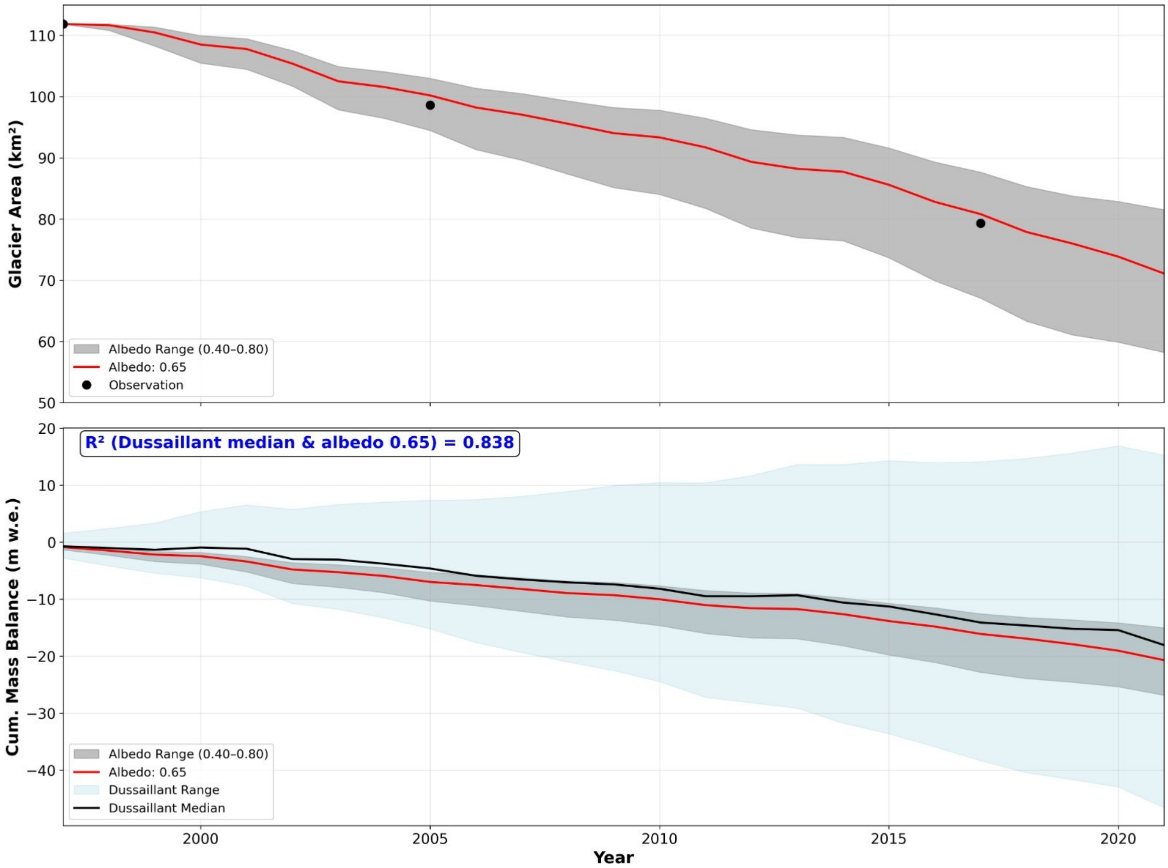

Figure 2 - Time series of glacier area (top panel) and mass balance (bottom panel) from 1997 to 2022 with modelled values (red line) and related uncertainty band (grey area), different albedo values from 0.4 to 0.8 (light blue area), glacier area observations (Galos et al., (2022), black dots) and annual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

3.2 Integrated hydrological model results

The hydrological model simulations considered both a dynamic and static glacier module. We compared their results to evaluate the 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).

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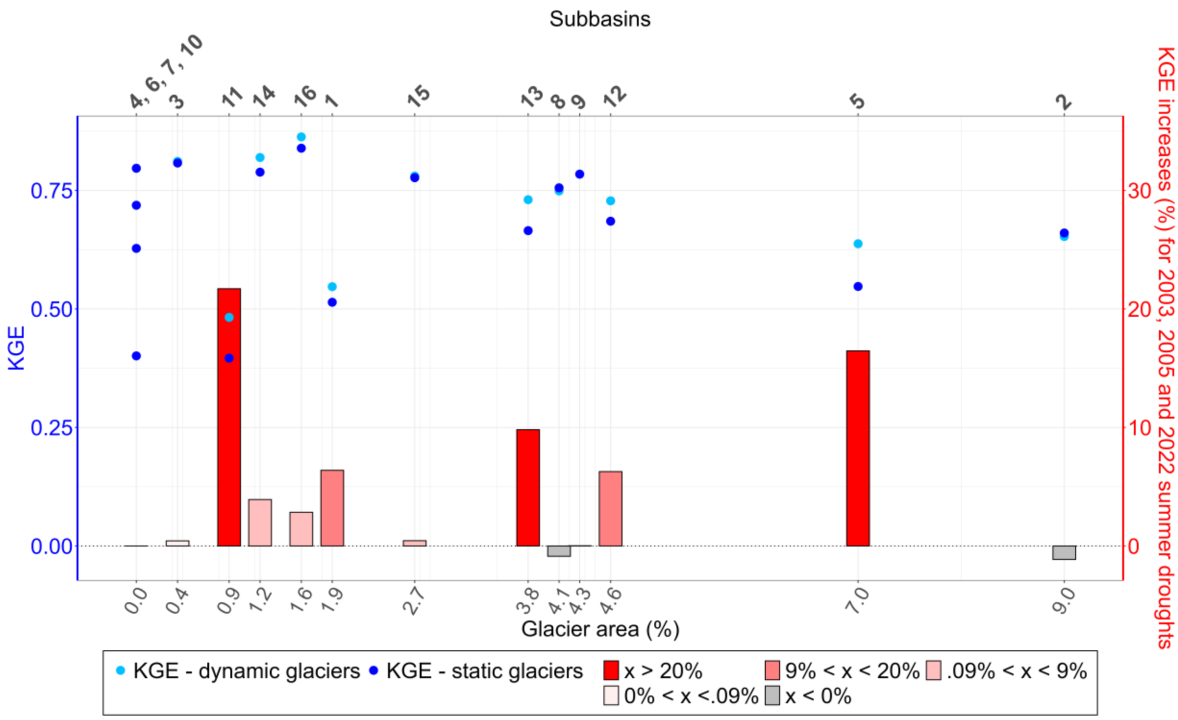

Figure 3 – The Kling-Gupta Efficiency (KGE) performance metric (left y-axis) for the streamflow simulation for the whole period (1998-2022), integrating a dynamic glacier module (light blue dots) and a static glacier module (blue dots) according to increasing values of glacier area over the each subbasin area on the x-axis. The bar plot represents KGE variation (%, right y-axis) between the two modelling setups, 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 slight increased, with values below +0.01, while for others it slightly decreases, 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 (more information in Tables 2s and 3s of the supplementary material). While the dynamic glacier module improved the representation of reduced glacier area conditions, it also implies a decrease of the glacier melt contribution, and hence 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

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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 % 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 decrease of 0.78 to 0.77 MBR in case of shift from static to the dynamic glacier module.

The findings confirm the previously identified tendency: subbasins with a positive runoff bias in the static glacier module improve their performance when including the dynamic module and vice-versa (information on KGE and MBR values for each subbasin in Table 2s and 3s of the supplementary material).

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 for the whole basin to support the temporal analysis of hydro-climatic variables driving droughts. Figure 4 (panel a) shows a heatmap of year-to-year 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) and 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 below-average precipitation during summers (e.g., years 2001 and 2014), while winters with below average snow can be compensated 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.

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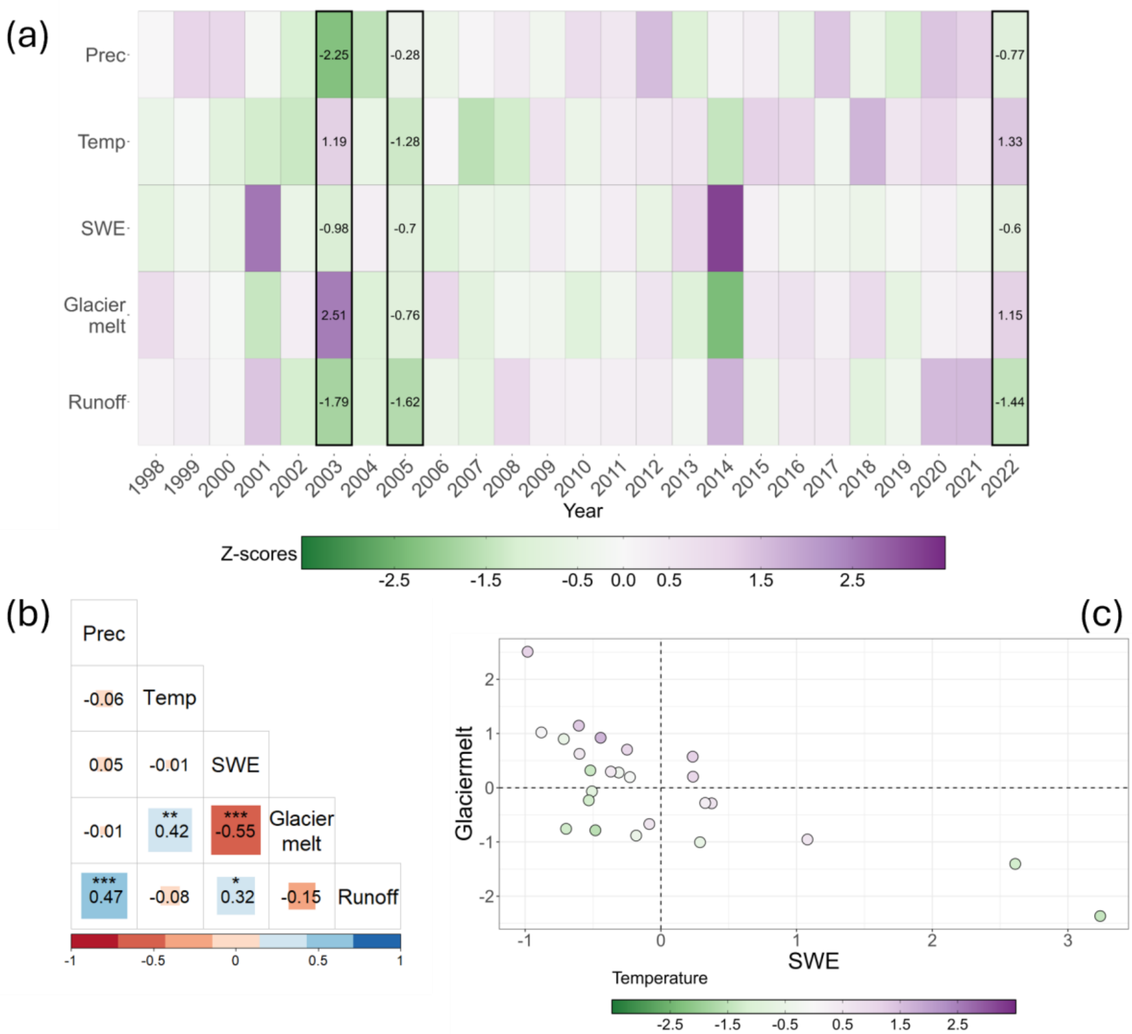

Figure 4 - Heatmap of the z-score values (green negative, purple positive) for the 5 hydro-climatic drivers of droughts for the whole upper Adige River Basin from 1998 to 2022 calculated for the summers months JJA and at end of June for SWE (panel a). Mann–Kendall correlations (from −1 to 1) between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

In particular, runoff shows a strong 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 strong and highly significant negative correlation (r=-0.55, p<0.001), recalling the blanketing effect of abundant snow cover preserving glacier from melting. On the

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

We further examined the apparent strong relationship between SWE, temperature, and glacier melt visualizing each summer in a scatterplot (Figure 4, panel c). High glaciers melt typically occurs with 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 drought in the 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 the average summer (JAS) runoff of 75 mm and *Val Sarentino* showed a -58% reduction of its average 68 mm of runoff. Other areas in the north-east also showed -50% reductions from an average runoff of 99 mm, despite increased glacier melt contributions. The runoff decline was primarily driven by strong precipitation deficits, which affected the entire area. The most severe deficit was observed in *Val d'Ultimo*, with a reduction of -77% for the average summer precipitation of 106 mm. Temperature anomalies were above the average, with mean increases of +0.89 °C across the upper Adige River Basin region. Snow Water Equivalent (SWE) at the end of June showed negative anomalies throughout the region, with 14 subbasins recording -100% compared to average summer values. These subbasins also registered the lowest average SWE in the 26-year simulation period. Due to the hot 2003 summer conditions, glacier melt strongly contributed across the region. Glacierized subbasins in the southwest showed +101% higher melt compared to the summer average values of 0.7–1.2 mm, while northeastern glaciers showed even stronger glacier melt of +180% above the average 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 -55% of its average 107 mm of runoff in *Val di Solda* and -54% of 81 mm in the lower part of the *Val di Solda*.

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

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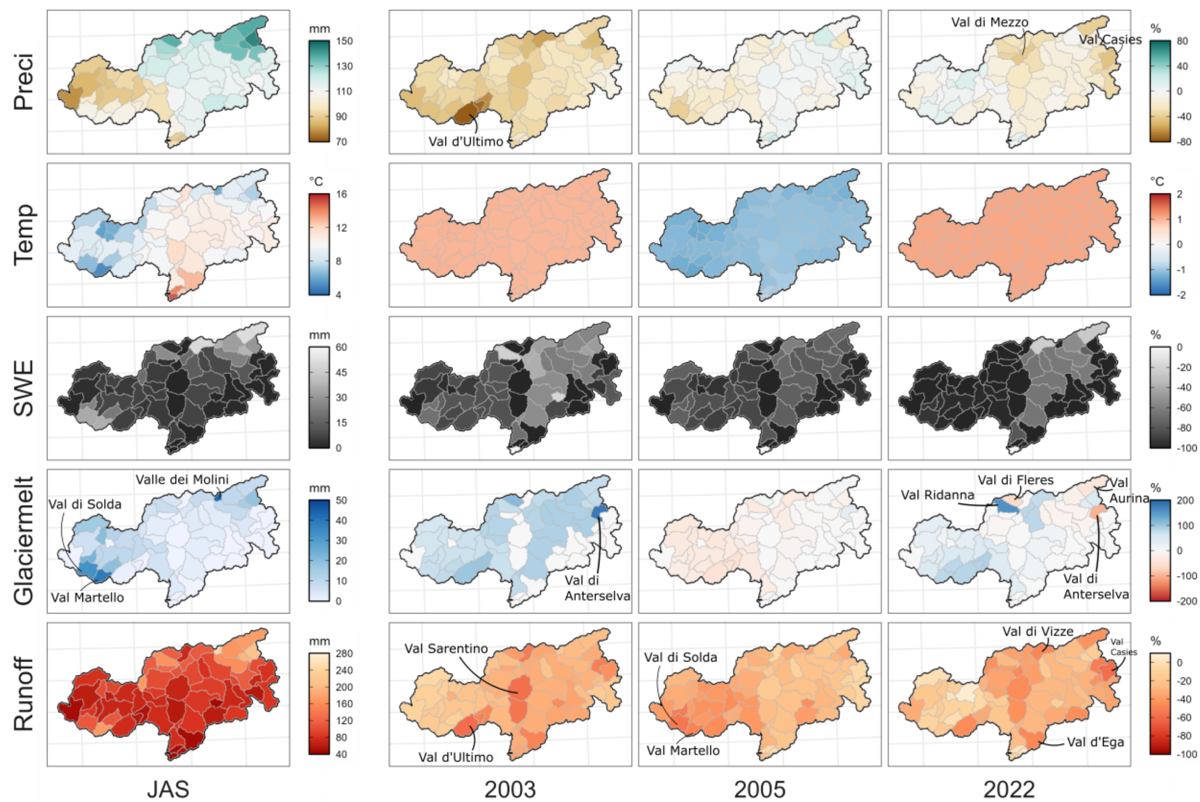

Figure 5 – Spatial representation of climatological mean (first column on the left) and anomalies (three columns on the right) computed for the average summer values from 1997-2023 within the upper Adige River Basin of the hydro-climatic variables. Only SWE consider values at the end of June. The anomalies 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. This colder-than-average summer had a notable impact on other hydrological components. Despite the cold temperatures in summer, SWE at the end of June was similar to 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 deficit showed -60% for the average summer runoff of 81 mm in *Val Casies*, -48% for 111 mm in *Val di Vizze*, -47% for 48 mm in *Val d'Ega* and -46% for average summer runoff of 75 mm in *Val d'Ultimo*. Precipitation

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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, for summer averages of 121 mm and 113 mm. Positive temperature anomalies 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 mid-eastern areas. Glacier melt was only partially affected by the warmer conditions and reduction of snow coverage. Increased glacier melt were showed in some areas, such as in *Val Ridanna*, which recorded +156% increase of its summer average of 7.1 mm. However, in other subbasins glacier melt was negative, including -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. The results reveal progressively increasing differences both in terms of glacier melt and runoff during the selected drought events, highlighting the growing influence of glacier recession. In particular, average summer glacier melt from the dynamical glacier module shows increasingly differences compared to the results of the 1997 constant glacier extent model: -7.81, -15.03 and -44.69% for the 3 selected drought years of 2003, 2005 and 2022, respectively, as detailed in Table 1.

Table 1 – Values of glacier melt and runoff for the three selected drought years of 2003, 2005 and 2022 at the Bronzolo gauge station and the percentage decrease of glacier melt contribution for the dynamic glacier module compared to the static module with 1997 levels.

	Average summer flow (mm)						Glacier melt % of runoff		
	Glacier melt			Runoff					
Years	Dynamic module	1997 glaciers	Δ [%]	Dynamic module	1997 glaciers	Δ [%]	Dynamic module	1997 glaciers	Δ [%]
2003	5.80	6.29	**-7.81**	49.68	50.17	**-0.99**	11.67	12.54	**-6.89**
2005	2.52	2.96	**-15.03**	51.86	52.32	**-0.87**	4.85	5.66	**-14.29**
2022	4.43	8.00	**-44.69**	54.19	57.79	**-6.23**	8.17	13.85	**-41.01**

Average summer runoff proved to be less sensitive to glacier retreat, with notable differences among the three simulated drought years. In 2003, runoff showed a change of –0.99% between dynamic and static simulations. In 2005, both scenarios provided similar runoff values mainly due to lower contributions from glaciers during the cold conditions characterizing the 2005 drought. In 2022, runoff decreased by -6.23% between the dynamic and

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static glacier simulation. The percentage contribution of glacier melt over the total runoff declined significantly over time between the dynamic and 1997 glacier modules. In 2003, the difference was –6.89%, increasing to –14.29% in 2005 and reaching –41.01% in 2022. While the reduction of glacier melt is mainly attributed to the shrinking glacier area, the increasing differences between the dynamic and 1997-glacier scenario indicate that the longer the simulation period and the greater the glacier retreat and hence the larger is the error in terms of glaciers mitigating summer drought introduced by considering a static glacier area.

4 Discussions

This study highlights the evolving role of glaciers in buffering hydrological responses to drought in the upper Adige River Basin. In the past major droughts, glacier melt contribution ranged between 4% and 13% of summer runoff, with variations according to the underlying temperature, precipitation, and SWE conditions. However, this buffering capacity is diminishing due to ongoing glacier retreat. Over the 26 years of simulation, glaciers in the upper Adige River Basin have been shrinking at an average rate of 1.95 km² per year, significantly reducing their ability to sustain summer flows during dry periods, as shown for the 2022 drought, where we estimated a reduction of 44% of the glacier melt contribution to runoff compared to the 1997 glacier extent.

We showed that 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). A reduced snow cover leads to a shorter duration of snow melt contribution while also earlier exposing glacier ice to high temperatures 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 droughts illustrates how the combination of varying cryospheric and climatic conditions shape runoff deficits. The 2003 drought, characterized by extreme precipitation deficits and high temperatures, resulted in the most severe runoff reductions in the upper Adige River basin (up to -60% in *Val d'Ultimo* and *Val Sarentino*). Despite the lowest runoff values, glacier melt provided a compensatory effect contributing to 12% of runoff and, hence mitigating the hydrological deficit. Differently, the 2005 drought, despite cooler temperatures and a lower precipitation deficit, was exacerbated by a significative reduction in snow and glacier melt. Such conditions highlight the importance of meltwater contributions to sustain streamflow during droughts. The 2022 drought, although similarly warm as 2003, showed lower glacier melt contributions (8%) than 2003. Our results show some differences from similar studies in other regions in the north of Italy. Results indicate that 2022 summer glacier melt contribution was 280% above the climatological mean, whereas Leone et al., (2025) found an anomaly of about 350% for other glacierized catchments (Valle d´Aosta and Valtellina) in northern Italy, indicating for all regions the importance of glacier melt during the 2022 drought. Despite the inherent uncertainty embedded in multiple factors such as glacier extent, elevation range, orientation as well as glacier melt data and model uncertainties, the implemented glacier dynamic module highlights the importance of areal glacier reduction affecting glacier melt contribution in 2022 compared to 2003.

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 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.

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5 Conclusions

Our analysis offers 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. Our analysis shows how the combination of multiple hydroclimatic variables (i.e., summer precipitation, temperature and especially snow water equivalent at the beginning of the summer) drives the amount of glacier melt mitigating to hydrological droughts.

Simulations in the upper Adige River basin in the Italian Alps for the 2003, 2005 and 2022 most severe droughts showed how glacier melt contributions ranged between 4 and 12% at the upper Adige closing section. The ongoing decrease of glacier extension (from 111 km2 in 1997 to 79 km2 in 2017) is leading to a significative decrease in glacier melt contribution to the overall runoff, especially during acute hot and dry events. This implies increasing vulnerabilities for water management in the area under drought conditions and with increasing downstream demand. Given the increasing emissions and global temperature and consequent glaciers disappearance (Van Tricht et al., 2025), our results call for proactive adaptation 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. We are in the process of releasing all the model code, input and output simulation data in an open access public repository.

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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 significative 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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