









Winter snow deficit was a harbinger of summer 2022 socio-hydrologic drought in the Po Basin, Italy

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Snow in mountainous regions is a key water resource from local to continental scales. However, the link between increasingly frequent snow droughts and socio-hydrologic impacts from headwaters to lowlands is not fully understood. To untangle this relationship, here we combine snow and climate reanalyses with a range of data of terrestrial water storage, streamflow, and emergency water-use restrictions for the archetypal 2022 snow drought in the Po basin (Italy). We find that a persistent high-pressure ridge during winter 2021–2022 translated into a –88% anomaly in peak snow water equivalent, intraseasonal snowmelt, and earlier melt-out dates. Compounded by reduced summer precipitation and importantly increased temperatures, this snow deficit led to the lowest terrestrial water storage on record in summer 2022. Emergency water-use restrictions were concurrent with the peak in snowmelt deficit in early summer, rather than the peak in precipitation deficit in mid-winter. This study highlights the contribution of snowmelt deficit in driving the 2022 socio-hydrologic drought in the Po Basin.

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Snow is a critical driver of the global water cycle, as it buffers winter precipitation into summer melt—when water demand peaks while precipitation declines^{1–3}. For example, this buffering effect accounts for as much as 53% of streamflow in the western United States^{4,5}, while peak Snow Water Equivalent (SWE) corresponds to 60+% of annual streamflow in the Italian Alps⁶ (SWE being a key metric in snow hydrology as it quantifies the amount of water in snow). Besides supporting water supply for 1.28 billion people living in mountains, which in turn occupy 23.5% of the global land surface⁷, the reliance of lowland societies on mountain water supply will also rise due to growing water consumption. Despite observed and future trends denoting a declining snow cover worldwide^{8–17}, snow will increasingly be a cornerstone of water security even in a warming climate⁹.

A declining snow cover will escalate impacts of climate change on water supply, including diminished accumulation on glaciers and thus accelerated melt¹⁸, less spring recharge and enhanced tree mortality^{19,20}, as well as a decrease in global streamflow^{1,21}. These processes will also intersect with trends portending more intense droughts²² in making water supply more exposed to inter-annual climatic variability and more frequent low-flow episodes^{23,24}. For ubiquitous biomes and societies that have historically relied on a consistent, secure access to the seasonal freshet, co-evolving with this combination of disappearing snow and more intense droughts will be a paradigm shift imperiling all aspects of life^{23,25}. Snow droughts thus emerge as a key feature of global dry periods in the 21st century, with far-reaching implications for water management²⁶.

Defined as periods of below-average snowpack, snow droughts are caused by a precipitation anomaly and/or above-average temperatures (cold vs. warm snow droughts, see refs. ^{26–29}). Recent studies have shown that such events have intensified over the northern Hemisphere since 1980³⁰, will increase in frequency in a warming climate²⁹, and are often exacerbated by rain-on-snow events and/or early melt³¹. Previous snow droughts have also demonstrated that they can lead to an escalation of impacts starting from snowmelt deficit³² and culminating in water scarcity and eventually emergency water-use restrictions (such as limitations to non-essential water uses or to water supply for specific areas or periods^{30,33–35}). Despite this empirical evidence, the mechanisms linking snow droughts in headwater basins to socio-hydrologic impacts in lowlands³⁶ remain largely unexplored^{27,30}. This leaves key knowledge gaps for future adaptation and mitigation of snow-dominated regions to this emerging risk: (i) to what extent do snow droughts affect water-storage anomalies, in addition to (expected) streamflow deficits? (ii) What is the role of snowmelt deficit, rather than low SWE, in driving water-supply anomalies³²? (iii) Do the spatial distribution and timing of snowmelt deficit bear a signature in escalating socio-hydrologic impacts of droughts in snow-dominated regions?

Here, we contribute to elucidating the socio-hydrologic implications of snow droughts in Alpine regions and how they unfold through space and time by drawing lessons from the intense 2021–2022 snow deficit across the headwaters of the Po river basin (Italy), the largest water basin in Italy, hosting ~25% of Italian population and 40% of the national gross domestic product³⁷. We first provide a spatially distributed perspective on 2021–2022 SWE anomalies across the elevation gradient of this basin through the IT-SNOW model reanalysis⁶ and show how this SWE deficit concurred not only to expected streamflow lows, but also to unprecedented terrestrial-water-storage anomalies since 2002. We then couple these data with an inventory of 886 municipal emergency water-use restrictions to highlight that such socio-hydrologic impacts were synchronous to the maximum snowmelt deficit, rather than winter precipitation deficit. These

results allowed us to identify the antecedent snow deficit as a key aggravating factor in the escalation of the 2022 socio-hydrologic drought in the Italian Alps, in addition to summer precipitation and temperature anomalies. Owing to this region hosting a variety of climates³⁸, and to this snow drought showing parallels with future trends²⁹, this event bears general implications for warming mountain regions worldwide.

Results

Context: synoptic circulation. The 2021–2022 winter drought in the Italian Alps originated from a quasi-stationary high-pressure ridge extending from northern Africa to the British Islands and from the Azores to Italy. In this regard, maximum anomalies for the 500-hPa geopotential height for the December 2021–February 2022 period were ~7.5 dam at the European scale (1991–2020 reference period, Fig. 1a). Synoptic patterns in Fig. 1a agree with ref. ³⁹, who instead considered the whole December 2021–August 2022 period; this highlights the persistence of this high-pressure ridge during 2021–2022. Mean seasonal pressure conditions at sea level confirmed these results, with maximum positive anomalies for the December 2021–February 2022 period of ~4.4 hPa (compared again to the 1991–2020 reference period). These anomalies were located across a continuous area from the north-eastern Atlantic Ocean to the western Mediterranean Sea (Fig. 1b).

December 2021–February 2022 mean 2-m air temperature was +0.53 °C warmer than the 1991–2020 reference period across Europe (Fig. 1c, +1.52 °C anomaly compared to the 1961–1990 period), with positive anomalies across a latitudinal band from 30°N and 60°N. Cumulative-precipitation anomalies showed an expected connection with the 500-hPa anomaly, in terms of a negative anomaly of up to –300 mm in December 2021–February 2022 cumulative precipitation that was centered between the north-eastern Atlantic Ocean and the western Mediterranean Sea (here again, 1991–2020 reference period). In relative terms, winter 2021–2022 in Europe saw precipitation deficits of up to –70% or more compared to mean seasonal precipitation for 1991–2020.

Patterns of SWE deficit. Emergence of these synoptic patterns in early 2022 led to three peculiar characteristics of the 2021–2022 snow drought in the Italian Alps, which we highlighted here using a spatially distributed model reanalysis of SWE from the real-world monitoring chain S3M Italy⁶. This operational chain has been extensively validated with a variety of in-situ and remote-sensing data (see the Methods) and routinely assimilates both in-situ snow depth and remote-sensing snow-covered area to deliver spatially distributed, optimal estimates of snow water resources across Italy (IT-SNOW reanalysis, see ref. ⁶).

The first peculiar feature of the 2021–2022 snow drought was a strikingly homogeneous spatial anomaly in reanalyzed SWE, with peaks in March-6 SWE well below –70% (Fig. 2a, 2011–2021 reference period, March 6 conventionally being the day of peak, spatially integrated SWE in Italy according to⁶). The only sub-regions with marginally lower anomalies were the north-western and north-eastern crests (between –60% and –20% at places). The Po river basin was the area with the most intense SWE anomaly (Fig. 2a), with a –88% ± 24% spatially average deficit compared to 2011–2021 (the ± margin refers to the spatial standard deviation of SWE anomaly). These results agree with evaluations by Colombo et al.⁴⁰, who recently reported that 2022 SWE across 15 point stations across the Italian Alps was the lowest on record since 1920/1930, and by ref. ⁴¹, who instead evaluated that the snow line in the Alps was several hundred meters higher than usual in 2022.

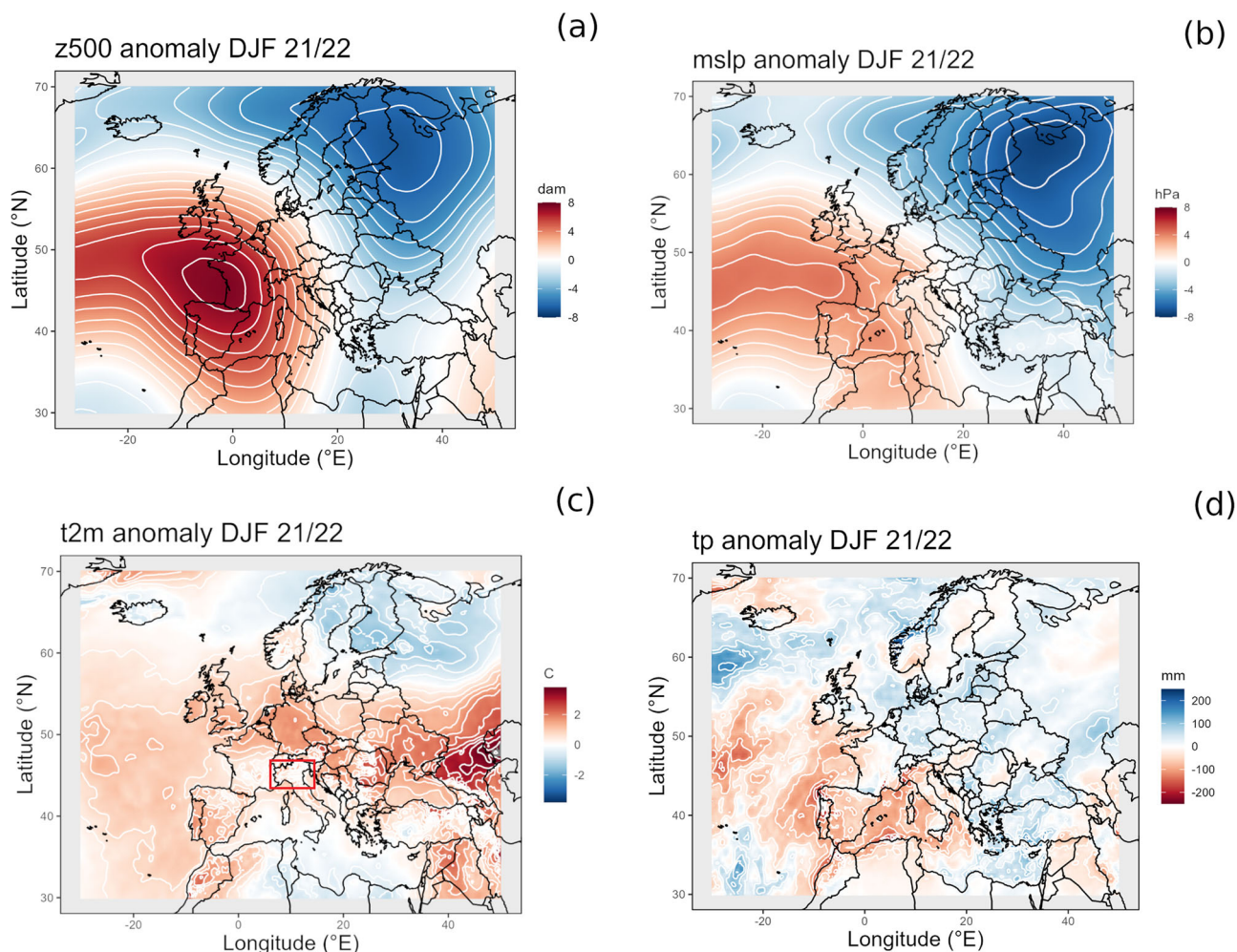


Fig. 1 Synoptic patterns leading to the 2021–2022 snow drought in the Italian Alps. **a–d** report anomalies with respect to the 1991–2020 reference period for mean December–February (DJF) 500-hPa geopotential height (z500), mean December–February sea-level pressure (mslp), mean December–February 2-m air temperature (t2m), and cumulative December–February precipitation (tp). The red bounding box in **(c)** delimits the region of the Po river basin. Data are from the ERA5 reanalysis (see Methods).

The second feature was a quasi-stationary reanalyzed SWE during mid-winter (Fig. 2b–f, results for the Po river basin), as opposed to SWE between 2011 and 2021 showing an increase up to peak accumulation in March⁶. This quasi-stationary SWE during mid-winter was the result of a dynamic equilibrium between only occasional snowfalls and frequent melt episodes due to higher-than-usual temperature. In this regard, mean-temperature anomalies for December 2021–February 2022 with respect to 2011–2021 increased with decreasing elevation across the Po river basin: from +0.18 °C between 2500 and 3000 m to +0.53 °C between 500 and 1000 m asl (see Fig. 2b–f, where we restricted the reference period for precipitation and temperature to 2011–2021 for sake of comparison with the SWE deficit). Meanwhile, cumulative-precipitation anomaly for the same period and area was between –54% and –38% across elevations, with also an increasing trend with decreasing elevation (see again Fig. 2b–f). This dynamic equilibrium, and in particular the positive temperature anomaly, led to SWE deficit being consistently larger than precipitation deficit for any elevation in Fig. 2b–f.

The third feature was an earlier-than-usual end of the reanalyzed snow season, defined as the day when spatially integrated SWE reached 2% of median historical peak SWE at a given elevation across the Po river basin. This trend was

particularly evident at very low (500–1500 m asl) and very high (2500–3000 m asl) elevations (see again Fig. 2b–f) and showed that melt-out date took place 97, 24, 21, 27, and 49 days earlier than during 2011–2021 at 500–1000 m asl, 1000–1500 m asl, 1500–2000 m asl, 2000–2500 m asl, and 2500–3000 m asl, respectively. We interpret this peak in the anticipation of melt-out date at very low and very high elevations as due to two separate mechanisms that made intermediate elevations less vulnerable in this regard. Below 1500 m, our data show frequent snow-melt episodes throughout winter that are compatible with prolonged periods above freezing due to warm temperatures (+0.53 °C to +0.40 °C mean-temperature anomalies in Fig. 2b, c). These periods of above-freezing temperature combined with cumulative-precipitation deficit (–54% to –53%) to cause climatic conditions that were essentially unsuitable to snow accumulation at low elevations. Above 2500 m asl, on the other hand, instances of above-freezing conditions and mid-winter snowmelt were much rarer, as substantiated by the quasi-stationary SWE in Fig. 2f. At the same time, snowmelt at those elevations took place in a period of the year - May - when ERA5 temperature anomalies with respect to 2011–2021 were substantially higher than in winter (+2.6 °C at 2500–3000 m asl); this spring heatwave likely played an accelerating role⁴².

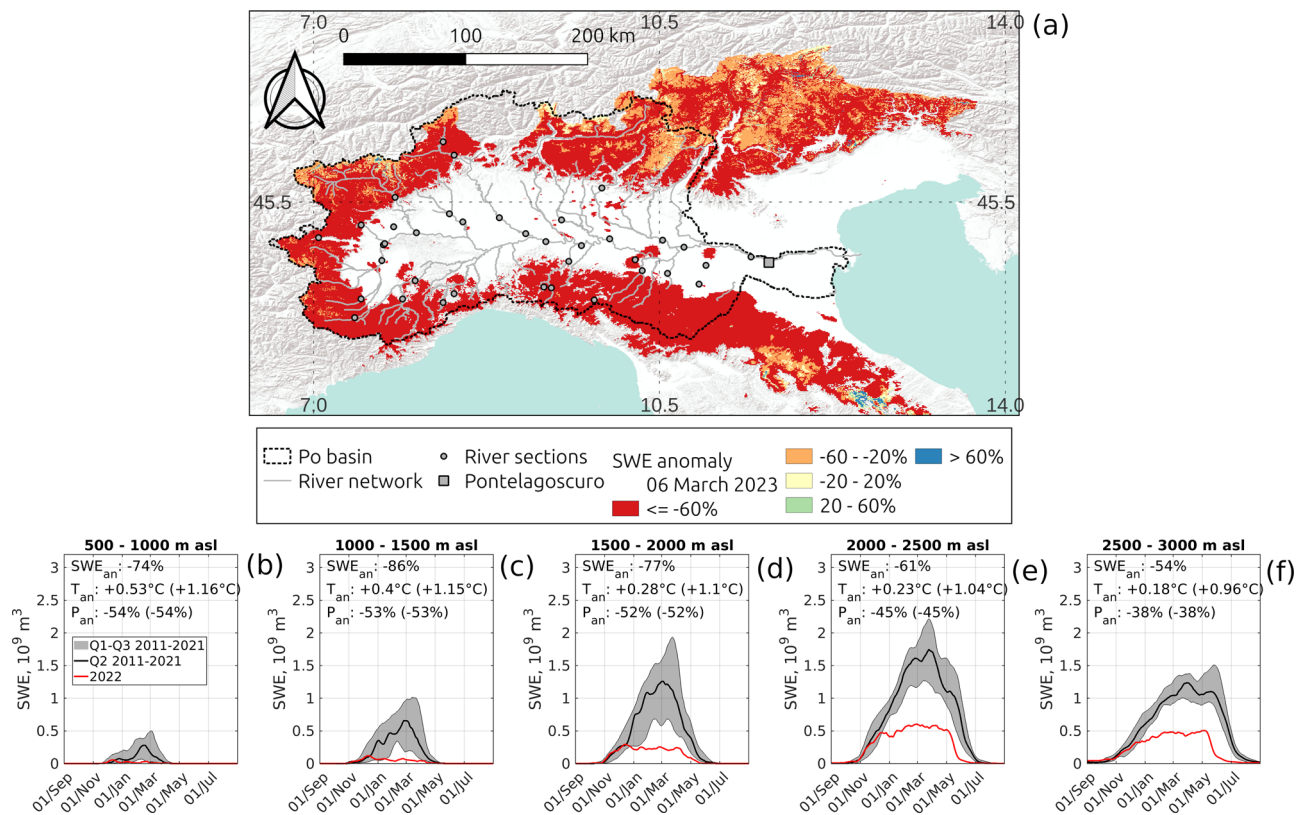


Fig. 2 The 2021–2022 Po basin snow drought through the lens of IT-SNOW⁶. **a** reports the spatial distribution of March-6 reanalyzed-SWE deficit in the broader context of the Italian Alps and northern Apennines (reference period 2011–2021, March 6 conventionally being the day of peak, spatially integrated SWE in Italy according to⁶). **b–f** report comparisons between 2021 and 2022 trajectories of spatially integrated SWE and 2011–2021 median (Q2) and first-third quartiles (Q1–Q3) for five elevation bands across this basin. SWE_{an}, T_{an}, and P_{an} are the anomalies of Snow Water Equivalent, mean 2-m air temperature, and cumulative precipitation for winter 2021–2022, compared to the reference period 2011–2021 (air temperature and precipitation are from ERA5, and SWE from IT-SNOW, see the Methods for details on data). Estimates of T_{an} and P_{an} between brackets refer to the 1991–2020 reference period for context. Note that SWE data do not include canton Ticino in Switzerland, which represents about 5% of the Po river basin (see again the Methods). River sections in this Figure are those considered in Section 2.3. Background map from the ESRI Terrain theme.

Socio-hydrologic impacts. The combination across this widespread SWE deficit, earlier-than-usual melt-out dates, and the concurrent precipitation and temperature anomalies triggered a clear escalation of socio-hydrologic impacts via storage and streamflow anomalies, as well as emergency water-use restrictions.

GRACE data for 2021–2022 across the Po river basin show unprecedented features compared to the 2002–2022 record (Fig. 3a, b). The seasonal mid-winter peak in terrestrial water storage in early 2022 was not only the lowest in the GRACE era, but it was also comparable in magnitude to several past summer minima; this is an indirect validation of SWE deficit as documented in Fig. 2. Along with this unusually low winter maximum, the following summer minimum was also the lowest on record. The range between winter maximum and summer minimum storage in 2022 was only slightly larger than previous years (−16.8 cm between March 2022 and August 2022, as opposed to a long-term mean and standard deviation of −15.5 and ± 4.5 cm, respectively), which suggests that the antecedent minimum during winter due to the meteorological-snow drought played a key contributing role in dictating the unprecedented low in terrestrial water storage in summer 2022. From a long-term perspective, GRACE data in Fig. 3a also show an historically declining water storage across the Po river basin (no-trend hypothesis rejected via Mann-Kendall test, significance level 0.05): 2021–22 storage was indeed stably below the first quartile for 2002–2021 (Fig. 3b). This decreasing trend in water storage

has multiple potential explanations, including an increase in the frequency of meteorological and snow droughts^{40,43}, enhanced evapotranspiration during dry and warm summers^{44,45} and increased irrigation⁴⁶.

In terms of streamflow deficit, correlating annual anomalies in September-to-August cumulative streamflow with spatially distributed annual anomalies in upstream March-6 SWE for 38 river sections along this basin³⁷ suggests a potential shift over recent years towards combined, more intense snow and streamflow droughts (see Fig. 3d, where the reference period was 2011–2021). The median anomaly across river sections was −20%, −27%, and −58% (streamflow) and −46%, −40%, and −82% (SWE) in 2012, 2017, and 2022, respectively, meaning that 2022 was the drought year with the highest anomalies in both variables compared to the recent 2012 and 2017 droughts (see^{43,47–49}, for context on previous droughts). Restricting these computations to headwater sections with no nested catchment returned even larger anomalies and a clearer trend towards an intensification of snow and streamflow droughts: −30%, −32%, and −70% (streamflow) and −46%, −71%, and −92% (SWE) in 2012, 2017, and 2022, respectively. Note that some of these sub-basins include canton Ticino in Switzerland, which represents about 5% of the Po river basin but is not included in our model reanalysis: in this regard, Fig. 3 show clustered results with no clear deviation from the global trend, thus suggesting a marginal impact of this simplification for our general scopes here (see the Methods for a further discussion on this). For context, Fig. 3c shows the

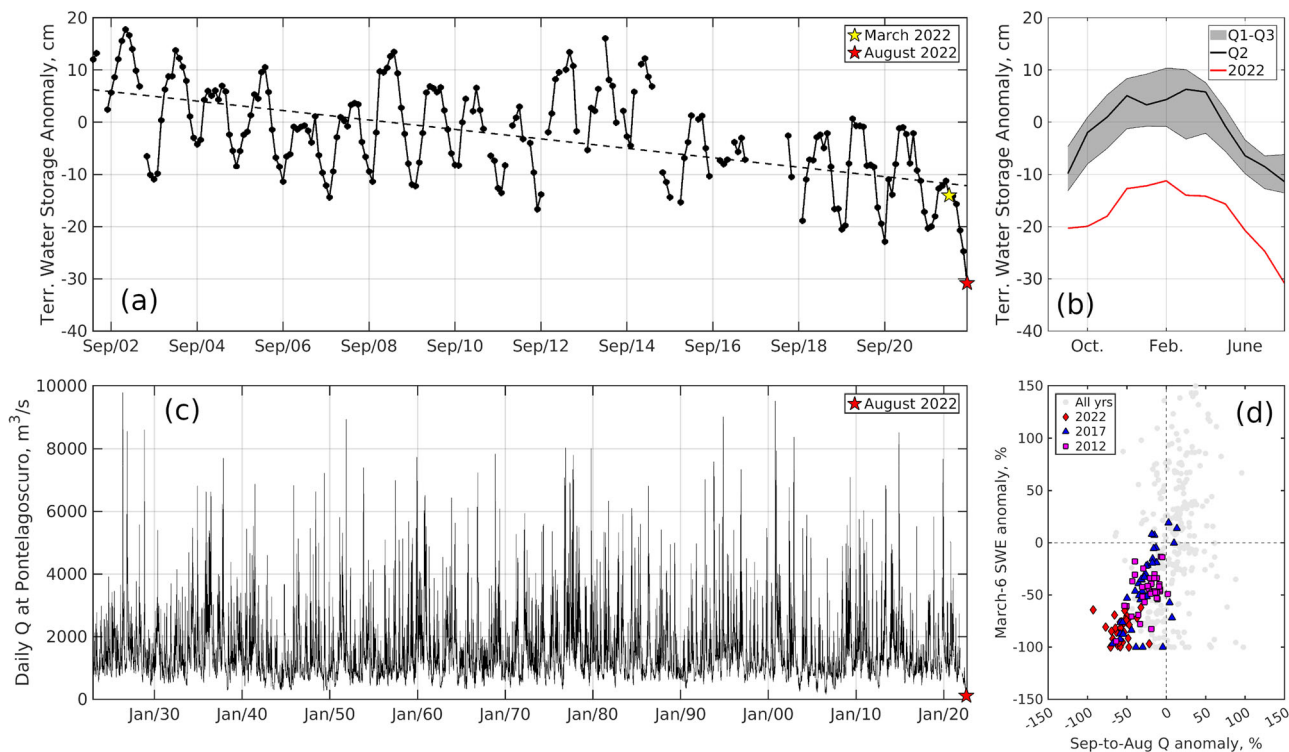


Fig. 3 Hydrologic impacts of the 2021–2022 snow drought in the Po river basin. **a** shows terrestrial water storage anomalies according to GRACE for the Po-river-basin area, 2002 through 2022, along with the statistically significant, linear trend (dashed line). **b** compares the trajectory of terrestrial water storage anomaly for 2021–2022 according to GRACE (red line) with 2002–2021 median (Q2) and first-third quartiles (Q1–Q3). **c** reports observed daily mean streamflow (Q) for the long-term, in-situ station at the closure section of the Po river basin at Pontelagoscuro (1923–2022). **d** correlates observed annual anomalies in September-to-August cumulative streamflow for 38 in-situ river sections across the Po river basin with annual anomalies in spatially distributed, upstream March-6 SWE (reference period: 2011–2021). In this panel, three recent droughts are highlighted: 2012, 2017, and 2022.

August-2022 historical minimum in daily discharge for the 1923–2022 data record at the closure section of Pontelagoscuro.

In the mixed rain-snow and heavily anthropogenic hydrology of northern Italy, clearly separating the water-supply effect of missed snowmelt from that of enhanced evapotranspiration, precipitation deficit, and/or irrigation is challenged by a lack of high-resolution data, particularly when it comes to water abstractions and use⁵⁰. In this regard, ref. ⁵⁰ have recently attributed the long-term negative trend in streamflow across the Po river basin to a decline in the fraction of precipitation falling as snow and in snowmelt, as well as an increase in evapotranspiration and irrigation (see also ref. ⁴⁵, on evapotranspiration enhancement during droughts in Europe). They also reported that summer 2022 yielded the lowest streamflow record along the Po river in the past two centuries, in the context of a declining trend in runoff since the ~1940s and a shift in seasonality towards an increase and a decline in spring and summer streamflow, respectively⁵⁰. ERA5 data used in this paper show a higher temperature anomaly during June–July–August 2022 than during winter 2021–2022 (+1.9 °C vs. +0.53 °C to +0.18 °C in Fig. 2, respectively), while the precipitation deficit was smaller during June–July–August 2022 than during winter 2021–2022 (–10% vs. –54% to –38% in Fig. 2, respectively, both anomalies with respect to 2011–2021). These results confirm the concurrent role of winter snow deficit and enhanced evapotranspiration in dictating the summer-2022 streamflow lows, with an additional, but likely smaller contribution from precipitation deficit.

Governance impacts for this event, in the form of municipal water-use emergency restrictions, point again to snowmelt deficit as a prime driver. Indeed, a comparison between the timing of maximum negative anomaly in monthly precipitation, maximum

negative anomaly in monthly snowmelt, maximum negative anomaly in monthly streamflow, and these water-use restrictions across the Po river basin for 2021–2022 unambiguously shows that peaks in both streamflow negative anomaly and importantly water-use restrictions were simultaneous to the peak in snowmelt negative anomaly, rather than in precipitation negative anomaly (Fig. 4, reference period is 2011–2021 for comparison across variables). The maximum deficit in precipitation was in January 2022 (Fig. 4a), while the month with the highest deficit in snowmelt across all elevations was June 2022 (Fig. 4b). Warm conditions during winter and the associated melt episodes even led to positive anomalies in snowmelt during mid-winter at all elevations but those below 1000 m asl (where SWE was minimal), which mitigated streamflow deficits in mid-winter, while exacerbating peak deficit in June 2022 (Fig. 4c). This snowmelt-deficit-driven streamflow drought⁵¹ determined a concentration of emergency water-use restrictions in June 2022, while such restrictions during spring were rare (Fig. 4d).

Clustering water-use emergency restrictions by publication period showed three distinct phases of the 2021–2022 socio-hydrologic drought that can again be clearly related to missed snowmelt (Fig. 5). During early stages of this drought (March to May 2022), scattered water-use emergency restrictions were issued mostly in headwater regions, where water supply is generally spring-fed and thus short-term resilience of local water security to droughts is low (e.g., see ref. ⁵²). The peak in water-use emergency restrictions between June and July 2022 was, instead, largely driven by lowland areas; this peak corresponded to missed freshet, a cornerstone of surface irrigation systems in Alpine lowlands that operates at temporal and spatial scales that are longer and larger, respectively, than those causing the early

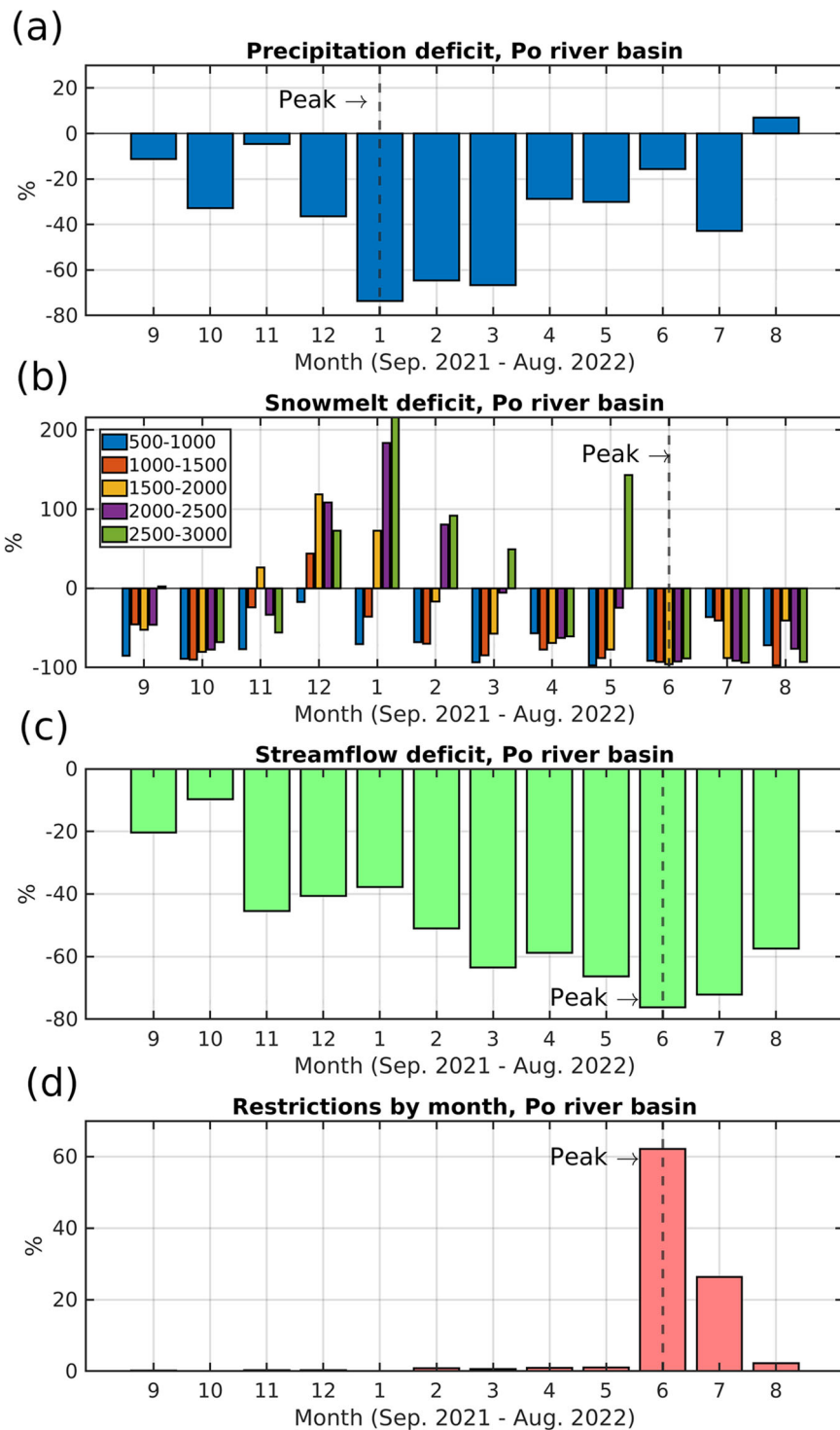


Fig. 4 Precipitation, snowmelt, & streamflow anomalies vs. emergency water restrictions in 2022. Comparison between monthly anomalies in cumulative precipitation from ERA5 (a), monthly anomalies in cumulative snowmelt for elevation bands according to IT-SNOW (b), monthly anomalies in cumulative streamflow at the in-situ station of Pontelagoscuero (closure section of the Po river basin, c), and the frequency distribution of emergency water-use restrictions -- all across the Po river basin. All anomalies in this Figure refer to 2021–2022 and are with respect to the 2011–2021 reference period for the sake of comparison across variables. A positive(negative) anomaly means a higher(lower)-than-usual monthly precipitation, snowmelt, or streamflow for that month -- and that elevation band in the case of snowmelt. In a–c, dashed lines represent the month with the maximum (absolute) anomaly for a given variable (average anomaly across elevation bands for snowmelt deficit). In (d), the dashed line represents the month with the highest concentration of new restrictions. Emergency water-use restrictions are from Piemonte, Valle d’Aosta, and Lombardia, which overall cover the vast majority of the Alpine portion of the Po river basin.

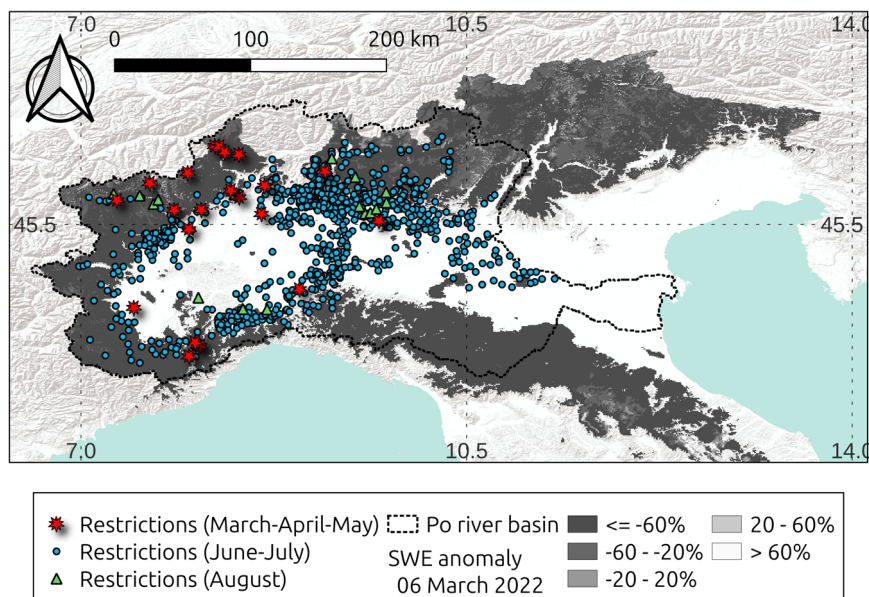


Fig. 5 Peak SWE anomaly vs. water restrictions. Comparison between the spatial distribution of municipal emergency water-use restrictions issued across the Po river basin in spring 2022 (March to May), early summer 2022 (June and July), and late summer (August 2022) and the spatial distribution of Mach-6 SWE deficit compared to the 2011–2021 reference period. Emergency water-use restrictions are from Piemonte, Valle d’Aosta, and Lombardia, which overall cover the vast majority of the Alpine portion of the Po river basin. Background map from the ESRI Terrain theme.

restrictions between March and May. In August 2022, we observed a renovated tendency towards issuing emergency water-use restrictions in mountain regions, which could be explained by the earlier-than-usual melt-out dates (Fig. 2b–f) leading to an exacerbation of summer streamflow deficits.

The minor role of emergency restrictions in headwaters between June and July 2022 could also be explained by a additional, compensation role of glacier melt in support to missing snowmelt. Pieces of evidence from the Swiss Alps show indeed that 2022 summer heatwaves led to at least 23 days of extreme melt, with 56% additional melt compared to the average Alpine summer¹⁸. Preliminary estimates from the glacier component of the same monitoring chain used in the present study for SWE show indeed that cumulative glacier melt across the Po river basin between September 2021 and August 2022 was equivalent to ~3% of annual streamflow, but this estimate increased to ~17% in August 2022. At the same time, previous findings suggest that glacier contribution to streamflow varies across catchment properties and antecedent conditions,⁵³ and decreases in importance with increasing spatial scales and increasing flowpath complexity⁵⁴.

Discussion

These findings contribute to further elucidating the role played by snow – and in particular snowmelt deficit—in contributing to socio-hydrological droughts. This evidence can inform a more resilient management of droughts in mixed rain-snow regions around the world.

From the perspective of snow accumulation and melt (the most frequent focus of previous studies on snow droughts, see refs. 26,28–30), Fig. 2 highlights different vulnerabilities of the seasonal snowpack across elevation gradients during the 2021–2022 snow drought. High elevations (say, above 2500 m asl) were more exposed to an earlier melt-out date than peak-SWE deficit compared to intermediate elevations (say, between 1500 m asl and 2500 m asl), while elevations below 1500 m asl saw weather conditions that simply impeded the development of the seasonal snowpack. While this vulnerability of low elevations

agrees with observed long-term trends in this region^{16,55} and with future scenarios for the Alps showing the potential disappearance of seasonal snow below ~1200 m asl by the end of the century^{13,56}, we provided here evidence of a different response of the seasonal snowpack to snow droughts in terms of peak-SWE deficit and/or melt-out date along elevation gradients. Peak SWE is closely connected with summer water volume^{4–6}, while melt-out date rules timing and decline of the seasonal freshet, as well as water availability for a variety of local ecosystem services¹⁹. A different impact of snow droughts on peak SWE and melt-out date along elevation gradients suggests the need for diversifying mitigation/adaptation strategies as a function of altitude.

From the perspective of total water storage and streamflow, Fig. 3 explains the historical low flow in summer 2022 across the Po river basin as the result of three overlapping mechanisms: the likewise historical deficit in SWE (and in precipitation) during the antecedent winter, the concurrent precipitation and temperature anomalies, and the multi-decadal decline in terrestrial water storage. The first mechanism is a further piece of evidence of the well known relationship between winter snow water resources and summer streamflow that has been at the foundation of forecasting approaches for summer water supply in snow-dominated regions for decades^{57,58}. The second mechanism also points to an already ample body of knowledge about evapotranspiration enhancement during droughts^{44,59}. The long-term decline in terrestrial water storage, instead, has additional policy implications, as it portends a potential, further intensification of summer low flows during future snow droughts if this trend continues. In the case of the Po river basin, this intensification may have already emerged from data (Fig. 3d). A decline of terrestrial water storage as observed in this paper for the Po river basin tallies with other global trends^{60–63}, and supports management options accounting for the intensification of summer low flows during snow droughts—especially in view of the supporting role of storage in mitigating impacts of meteorological droughts⁴⁹.

From the perspective of socio-hydrologic impacts, our inventory shows that municipal emergency water-use restrictions in summer 2022 affected more than 6.1 million people across the Po

river basin. The fact that emergency water-use restrictions were issued in conjunction with the peak in snowmelt deficit rather than precipitation deficit (Figs. 4 and 5), along with the fact that this snowmelt deficit was the result of an antecedent lack of winter snow, opens a clear window of opportunity to develop seasonal early-warning systems of socio-hydrologic droughts in snow-dominated regions. In this regard, it is worth noting that the lack of snow during the 2021–2022 drought in the Po river basin emerged as a precursor of both timing (Fig. 4) and location (Fig. 5) of water-use restrictions, with an evident temporal trajectory from early restrictions in headwater catchments to late restrictions in lowlands that again points to SWE as a critical indicator for future impacts. While estimating SWE in real time and across the landscape has historically been challenging^{2,64}, state-of-the-art satellite retrievals⁶⁵ and hyper-resolution models currently allow one to resolve SWE patterns at resolution well below 1 km^{26,66}. These tools represent the most promising solution for a more quantitative forecasting of snow-drought impacts that could assist more resilient governance—a highly needed step in the wake of the observed increase in snowmelt-deficit hydrologic droughts across the Alpine water towers³² and the supportive role of snow for worldwide water and food supply⁶⁷.

Methods

Synoptic circulation. We characterized synoptic weather patterns during the 2021–2022 snow drought in the Italian Alps using data from the ECMWF Reanalysis v5 (ERA5⁶⁸). This reanalysis comprises hourly spatial snapshots of all relevant atmospheric variables for 137 vertical levels and with a spatial resolution of ~30 km. More information about ERA5 and access to data are available at the following link: <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5> (last access: July 7, 2023).

For the purpose of characterizing large-scale temperature and precipitation anomalies across Europe, as well as their link with atmospheric pressure (Fig. 1), we considered the following four fields: 500-hPa geopotential height, mean-sea-level pressure, 2-m temperature, and precipitation (defined in this study as the sum of snowfall and rainfall). We processed hourly data over the European domain and computed mean 500-hPa geopotential height, mean-sea-level pressure, and 2-m temperature, as well as cumulative precipitation for the period December 1, 2021 to February 28, 2022. We considered here the December–February period as it represents the reference period of meteorological winters in the northern Hemisphere. Also, results in Fig. 2 and in ref. 6 show that the bulk of snow accumulation in Italy takes place during this three-month window.

2021–2022 statistics were then compared with their long-term counterparts for the standard reference period 1991 to 2020 (see WMO Guidelines at https://library.wmo.int/doc_num.php?explnum_id=4166, last access on July 19, 2023) to compute both dimensional anomalies as follows:

$$X'_{an} = X_{2021-2022} - \bar{X}_{1991-2020}, \quad (1)$$

and percentage anomalies as follows:

$$X_{an}(\%) = \frac{(X_{2021-2022} - \bar{X}_{1991-2020})}{\bar{X}_{1991-2020}} \times 100, \quad (2)$$

where $X_{2021-2022}$ is a given variable for the 2021–2022 winter period (e.g., mean 2-m temperature or cumulative precipitation), and $\bar{X}_{1991-2020}$ is its long-term counterpart for the same season. This definition was applied to all the four variables above.

In this paper, we generally used percentage anomalies as their adimensional nature allowed for an explicit comparison across variables. The only two exceptions were Fig. 1, where we

considered dimensional anomalies for comparison with previous literature on this event³⁹, and in general for air temperature throughout the study given the widespread use of such dimensional metrics in the context of climate-change scenarios of this variable⁶⁹. For conciseness, both metrics are referred to as simply “anomaly” in the main text.

For comparison with snow anomalies (Fig. 2), the reference period in Equation (2) was restricted to overlap the shorter reference period available for SWE (see next Section): 2011–2021 (this holds for winter, June–July–August, and May anomalies). The same reference period was also used for comparison across precipitation deficit, snowmelt deficit, streamflow deficit, and emergency water-use restrictions (Fig. 4). In that case, Eq. (2) was further adapted to use monthly rather than seasonal statistics. Besides these changes, Eqs. (1)–(2) represent the reference for all anomalies computed in this paper.

Snow water equivalent. Spatially distributed estimates of SWE were from the modeling monitoring chain S3M Italy developed by CIMA Research Foundation for the Italian Civil Protection System within the FloodPROOFS suite^{6,70}. This system provides operational, daily snapshots of modeled SWE, snow depth, bulk-snow density, snow liquid-water content across the whole of the Italian territory, at both 200 m and 500 m. S3M Italy is fed by real-time, hourly weather inputs of precipitation, air temperature, relative humidity, and incoming shortwave radiation obtained by the spatialization of in-situ measurement stations managed by regional administrations and the Italian Civil Protection Department. These stations cover the full geographical and elevation range of Italy (see an example of station distribution and spatialization results in ref. 6, Fig. 2). Input data are used to force a spatially distributed, physics-based snow and glacier model, S3M⁷¹. During winter (December to April, inclusive), S3M Italy also assimilates daily maps of snow depth obtained from the spatialization of in-situ measurements from 300+ ultrasonic depth sensors managed by regional administrations and 800+ manual surveys by AINEVA (Associazione Interregionale di coordinamento e documentazione per i problemi inerenti alla neve e alle valanghe), as well as daily maps of snow-covered area obtained by blending Sentinel-2, MODIS, and Eumetsat H SAF data (see again ref. 6).

S3M Italy has been extensively validated using a variety of remote-sensing and in-situ data, including 1-km Sentinel-1-based maps of snow depth⁶⁵, multi-year peak-accumulation snow courses and daily to weekly manual measurements at recurring locations in Aosta valley (north-western Italian Alps), weekly estimates of snow depth and SWE obtained by running the physics-based multi-layer SNOWPACK model⁷² at medium elevation and measurements of snow depth and SWE collected between May and June on glacier terrains in Lombardia (central Italian Alps), and daily to weekly manual measurements at four recurring locations for avalanche and water supply forecasting in Molise (southern Apennines). This validation yielded predictive performances that are in line with current standards in snow hydrology, including little to no mean bias compared to Sentinel-1 maps and root mean square errors of ~30–60 cm and ~90–300 mm for in situ, measured snow depth and SWE, respectively. More details on this dataset and on the evaluation protocol can be found in⁶, including an indirect validation using streamflow data showing that estimates of peak SWE for 102 basins across the country were expectedly well correlated with annual streamflow (Pearson’s correlation coefficient of 0.87).

In the context of this work, we used the collection of 500-m S3M-Italy outputs coming from IT-SNOW, the first, open-source and sub-kilometer reanalysis of the Italian SWE^{6,73}. The

originally available period of IT-SNOW went from September 1, 2010 to August 31, 2021, which we extended through August 31, 2022⁷³. Based on this dataset, we first computed a spatially distributed anomaly for March-6 2022 SWE across the Italian Alps (Fig. 2a) by adapting Eq. (2) to SWE and to the reference period 2011–2021. We chose March 6 as it corresponds to the average day of peak, spatially integrated SWE in Italy according to results by⁶, who converted pixelwise SWE to m³ by taking into account pixel area and then accumulated this volume of water in snow across the whole of the Italian territory to obtain trajectories of daily, total SWE across the country (see details in ref. ⁶). Second, we computed seasonal trajectories of spatially integrated SWE across the Po river basin for all snow seasons between 2010–2011 and 2021–2022 and for five elevation bands (Fig. 2b–f), using the same approach outlined before for spatially integrated Italian SWE. Third, we used these trajectories by elevation bands to reconstruct snowmelt based on day-to-day differentiation of SWE and then to estimate monthly anomalies based again on the adaptation of Eq. (2) to snowmelt and the reference period 2011–2021 (Fig. 4b). Fourth, we computed annual anomalies in basin-wide, upstream March-6 SWE for all seasons between 2010–2011 and 2021–2022 and 38 sub-basins of the Po river basin for which concurrent streamflow data were available (see Fig. 3d and the next Section). For this last computation, the reference period was again 2011–2021: while this means that all annual anomalies in March-6 SWE but those for 2022 overlapped with the reference period, we preferred this over other options (such as extending the reference period to 2022) for consistency with all other SWE-related computations in this study.

Due to a lack of input and assimilation data, S3M Italy does not include canton Ticino in Switzerland, although this area belongs to the Po river basin. We expect this to have limited impacts on the assessment of SWE anomaly, as canton Ticino only represents about 5% of the Po river basin and its SWE conditions are generally in line with those of the Italian Alps, owing to Canton Ticino being located south of the main north-south Alpine divide⁷⁴.

For the comparison between glacier melt and streamflow, we used the glacier component of S3M Italy. This component relies on a simplified representation of glaciers that does not take into account movement or mass balance. Thus such estimates should be considered as preliminary at this stage. Details on this glacier model are available in⁷¹.

Terrestrial water storage and streamflow. We derived terrestrial-water-storage anomalies from the NASA Gravity Recovery and Climate Experiment (GRACE) and its Follow-On satellite mission (GRACE-FO,^{75,76} see <https://podaac.jpl.nasa.gov/dataset/and> <https://search.earthdata.nasa.gov/> last access on July 8, 2023). These missions provide global retrievals of terrestrial water storage, which includes groundwater, soil moisture, snow, and surface water^{77–80}. The retrievals, which are based on measurements of the Earth's gravity field, are provided in terms of changes relative to a time-mean reference value. Because of this, GRACE and GRACE-FO only provide changes in terrestrial water storage relative to a time mean reference value, but not a long-term mean climatology, so biases cannot be evaluated. Retrievals are reasonably accurate (~10–30 mm error standard deviation) but have coarse resolution in time (monthly) and space (~300–400 km at mid-latitudes, see ref. ⁷⁷).

The data used in this study are monthly global anomalies relative to the mean of the reference period 2004–2009 and were processed at the NASA Jet Propulsion Laboratory using the Mascon approach (RL06.1Mv03, see ref. ⁷⁶). We used data covering the period April 2002 to August 2022. The time series of

terrestrial water storage was the spatial average of the mascon solutions collocated within the boundary domains of the Po river basin (bounding box: 44.25°N, 46.25°N, 7.25°E, 12.25°E). While these mascons include area outside the Po river basin, we did not restrict the spatial mean to the Po river basin boundaries in an attempt to take into account uncertainty in groundwater flow paths, which may indeed exceed the surface boundaries of the Po river basin. Our spatial average provides a regional view, including unknown groundwater flow paths.

Daily mean streamflow for the Po river basin at Pontelagoscuro for 1923–2022 (Fig. 3c) was reconstructed from the Annali Idrologici di Emilia-Romagna, periodical bulletins of hydrologic conditions published by the Italian regional administrations⁸¹. Annual anomalies in cumulative September-to-August streamflow for all years between 2010–2011 and 2021–2022 and 38 sub-basins of the Po river basin (Fig. 3d) were instead computed based on daily streamflow data collected through the database of the Italian Civil Protection and regional hydrometeorological offices^{37,49}.

We acknowledge that streamflow data across the Po river basin are locally/seasonally affected by anthropogenic processes such as irrigation: this theme has already emerged in previous studies about the water balance of the Po river basin³⁷, but only early approaches are currently available to correct data in this regard⁸².

Like for SWE, the reference period of streamflow anomalies was 2011–2021: while this means that all annual anomalies in September-to-August cumulative streamflow but those for 2022 overlapped with the reference period, we preferred this over other options (such as extending the reference period to 2022) for consistency with SWE-related computations above.

Emergency water-use restrictions. Water-use restrictions in Italy come in different forms and are issued by various administrative levels (from the local to the national one). Here, we focused on “ordinanze sindacali”, that is, measures issued by local mayors in the wake of serious hazards that can challenge the safety of citizens. According to the Italian law, these measures must be clearly justified by unforeseen and urgent events and are the most local (and thus most spatially distributed) form of emergency management – an ideal source to gauge spatially distributed socio-hydrologic impacts of the 2021–2022 snow drought.

We performed the inventory of such emergency water-use restrictions across the Po river basin by focusing on three administrative regions in particular, which overall cover the vast majority of the Alpine portion of the Po river basin: Piemonte, Valle d'Aosta, and Lombardia. Given that no centralized database for such restrictions exist in Italy, we consulted a variety of sources and followed a hierarchical approach (from the highest to the lowest level of administration) that allowed us to validate and cross-check information multiple times. A first list of restrictions was obtained by contacting personnel within regional administrations in charge of monitoring water resources and/or civil protection. These initial lists were then compared with those provided by peripheral water-resources-management agencies (e.g., Ambiti Territoriali Ottimali, public bodies integrating provinces, cities, and mountain communities with a specific focus, such as water management). We further expanded this list by consulting municipal repositories of local regulations (in Italian, Albi Comunali), as well as by contacting local administrations (via email and/or phone calls) and surveying specialized websites and newspapers.

This survey allowed us to collect a unique, albeit likely non-exhaustive, list of 886 water-use restrictions for the Po river basin out of a longer list of 1100+ instances of emergency water-related regulations. Typical water-use restrictions include

limitations on water availability for non-essential uses, on water supply from public fountains, on available water for irrigation, on water supply for specific areas of a city or for specific periods of the day. The remainder included instead other mandates related to water use, such as advising the public on boiling water before use, which might not be related to water scarcity only, but also to other environmental factors; thus they were neglected. For each of the final 886 emergency water-use restrictions, we also identified the exact date of publication.

While socio-hydrologic impacts of droughts are multifaceted and can involve agriculture, hydropower, industries, ecosystems, recreation, and public water supply⁵¹, we chose emergency water-use restrictions as a measure of such impacts for a variety of reasons that make them particularly suited to our scopes. First of all, water-use restrictions as issued by mayors are the most high-resolution form of impact report on water supply, because city administrations are the most frequent form of local authority in Italy. Second, these restrictions generally follow a standard, somewhat consistent format that facilitates comparisons and categorizations. Third, such impacts on water supply are among the most frequently reported ones in Europe⁴⁸, which further supports this choice.

Data availability

ERA5 data are available at the following link: <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5> (last access: July 7, 2023⁶⁸). Outputs by S3M Italy and IT-SNOW are available at <https://zenodo.org/records/10402760> (last access: December 20, 2023⁷³). GRACE data are available at <https://podaac.jpl.nasa.gov/dataset/> (last access: July 7, 2023^{75,76}). Long-term streamflow data at Pontelagoscuro are available through the Annali Idrologici di Emilia-Romagna⁸¹, while daily data for all other sections are available through the respective regional hydrometeorological offices. Emergency water-use restrictions are available through the various municipal administrations of Valle d'Aosta, Lombardia, and Piemonte. Streamflow data and emergency water-use restrictions were made available by such third parties, which retain copyright.

Code availability

S3M Italy is the output of an open-access snow model^{83,84}.

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Author contributions

Francesco Avanzi conceived the study, computed Snow-Water-Equivalent anomalies, coordinated data analysis, and drafted the manuscript. Francesca Munerol conceived the study, collected emergency-water-use-restriction data, performed the consequent forensic investigation, and drafted the manuscript. Massimo Milelli processed ERA5 data, computed 500-hPa, mean-sea-level-pressure, 2-m-temperature, and precipitation anomalies, and contributed to data analysis and discussion. Simone Gabellani contributed to data analysis and discussion. Christian Massari collected and processed streamflow data, and contributed to data analysis and discussion. Manuela Giroto processed terrestrial-water-storage data from GRACE and contributed to data analysis and discussion. Giulia Bruno collected and processed streamflow data, and contributed to data analysis and discussion. Edoardo Cremonese, Marta Galvagno, Umberto Morra di Cella, Lauro Rossi, Marco Altamura and Luca Ferraris, contributed to data analysis and discussion.

Competing interests

The authors declare no competing interests.

Additional information

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