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Climate-induced drying of Lake Azzurro (Central Italian Alps): impacts and future projections

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Alpine lakes have proven particularly sensitive to climate change, especially to fluctuations in air temperature and precipitation. Such variations can affect the ecosystem services provided by mountain lakes, like freshwater supply for local population and regulation of nutrient cycling that supports biodiversity, impacting on a vital resource which serves as essential habitat for a wide range of plant and animal species as well. This study aims to examine the impacts of climate variability on Lake Azzurro, a small lake located in the municipality of Campodolcino in the Central Italian Alps. The lake follows a natural seasonal cycle, typically characterized by a reduction of water level from late summer to mid-autumn, followed by reappearance in late spring. However, since the early 2000s, it has experienced prolonged dry periods, specifically in 2005–2006, 2018, and 2022–2023. To investigate the relationship between lake's existence and climatological variables, weather data from a nearby meteorological station were analyzed. This was followed by an impact assessment based on high-resolution climate projections (RCP 4.5 and RCP 8.5 scenarios) derived from Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) models, with horizontal resolutions of 2.2 and 8 km, extending through the end of the century. The results suggest an increasing frequency of drying events that could lead to a progressive loss of this ecologically and culturally significant lake. Such a decline would have substantial implications for the ecosystem services it provides to both the local community and the broader region. The findings underscore an urgency for raising public awareness of the lake's vulnerability, a call for the development of comprehensive mitigation strategies, such as improved water resource management, biodiversity conservation, and the promotion of sustainable land-use practices within the lake's catchment area.

KEYWORDS
global warming, mountain lakes, drought, alpine environment, ecosystem services, water scarcity

1 Introduction

The ecosystem of the Alps is a vital resource for people living in this region (Spehn et al., 2010). Its landscape provides a wide range of goods and services, commonly known as ecosystem services (ES) (Costanza et al., 1997; Costanza, 2008; 2020; Babì Almenar et al., 2018; Remme et al., 2024), including water resources, carbon storage, and biodiversity habitats. Alpine ecosystems are increasingly threatened by climate change (Gobiet et al., 2014), which is profoundly affecting the benefits they offer. One of the most significant impacts is the melting of glaciers and snowpack (Soncini et al., 2017; Aili et al., 2019), which reduces freshwater availability and increases the risk of flooding and landslides downstream (Allamano et al., 2009; de Jong, 2015). Even the tourism industry, an important economic sector in this territory, is adversely affected, as rising temperatures lead to reduced snow cover and a shorter skiing season (Steiger et al., 2017; Vorkauf et al., 2024; François et al., 2023).

Alpine lakes, located at intermediate elevations (1,500–2,000 m a.s.l.), may exhibit greater sensitivity to global warming than those at higher altitudes, due to the pronounced influence of air temperature on ice cover duration (Bertoldi et al., 2023), precipitation patterns, and the persistence of surface water (Thuiller et al., 2005a; Boggero et al., 2019). Their biodiversity is a testament to nature's resilience and adaptability. The aquatic life in these lakes displays remarkable adaptations, with species evolving dedicated physiological and behavioral traits to cope with the cold temperatures and low oxygen levels (Pastorino and Prearo, 2020; Rogora et al., 2020). From tiny invertebrates, such as dragonflies, mayflies and chironomid larvae to iconic fish species like trout, these lakes harbor a variety of organisms that have found their ecological niche in this unique habitat. The interconnectedness of these ecosystems is paramount for maintaining the delicate balance of biodiversity and preserving the ecological integrity of mountain lake habitats (Catalan, et al., 2009). Moreover, the cultural heritage associated with the natural environment is at risk, as changing environments may undermine the cultural significance of regional landscapes and affect the identity and wellbeing of local communities, e.g., permanent and second home residents, tourists, etc. (Pyke et al., 2010). In fact, alpine lakes provide a wide array of ES, defined as the benefits that ecosystems provide to human welfare, with widely adopted frameworks including the Millennium Ecosystem Assessment (MEA), the Economics of Ecosystems and Biodiversity (TEEB), and the Common International Classification of Ecosystem Services (CICES). Specifically, these lakes supply freshwater essential for wildlife and support habitat for species such as alpine amphibians and large mammals, while maintaining plant diversity that contributes to soil stabilization and microclimate regulation (Tiberti et al., 2025). Beyond these ecological functions, mountain lakes hold cultural and historical significance, offering recreational opportunities, inspiration for artistic and literary works, and natural laboratories for scientific research. These services illustrate how these lakes link ecological integrity with the social identity and heritage of local communities.

The study is focused on Lake Azzurro, a small water body situated in Campodolcino town, within the Valtellina area in the Central Italian Alps. This lake plays a crucial role in providing a diverse range of ES that can be grouped into three main categories according to the CICES: provisioning, regulating, and cultural; for a complete description of these service types, see MEA (2005) and Haines-Young and Potschin (2013). As this lake is a closed catchment with no outlets that could maintain a stable hydrological balance, it relies almost entirely on precipitation and snowmelt as basin recharge mechanism. Its natural cycle, i.e., water recharge-discharge, involves a decrease in water level between late summer and mid-autumn and a refill by late spring. However, starting from the early 2000s, the lake has remained completely dry for prolonged periods during the years 2005–2006, 2018, and 2022–2023.

To investigate the lake's fluctuations in relation to local climatic variability, we first reconstructed the local climatology by analyzing available data from nearby meteorological monitoring sites. In particular, the station managed by the A2A company, being the closest to the study area, after a homogenization process, has provided a comprehensive dataset of historical observations, including precipitation (rainfall and snowfall) from the sixties, and temperature records spanning the period 1981–2024, enabling a robust climate analysis. A second phase of the study employed high-resolution climate projections, with spatial resolutions of 2.2 and 8 km, derived from the climate models by CMCC; these simulations help to understand the climate system and make predictions about future climate conditions under Representative Concentration Pathway (RCP) scenarios (Moss et al., 2010). Although there are some intrinsic uncertainties, they provide useful data for adaptation and mitigation planning for governments and organizations. In this study, two scenarios were considered: RCP4.5, a stabilization pathway without overshoot leading to a radiative forcing of 4.5 W/m^2 (approximately 650 ppm CO_2 eq.) by 2070, and RCP8.5, a high-emission scenario projecting a continuous rise in radiative forcing reaching 8.5 W/m^2 (approximately 1,370 ppm CO_2 eq.) by 2100. Based on these climate projections, a qualitative impact assessment is, finally, conducted on the ES provided by the lake and its ecological value.

The research aims to find an association between lake's disappearance and temperature-precipitation regime changes by looking at historical data, and, once fixed strategy was, to discuss the predicted effects of climate change with future scenarios on different ES the lake provides. In particular, this work aims to answer the following research questions: (i) Is it possible to establish a significant relationship between climatological data and the lake's disappearance? (ii) What could happen to the Lake Azzurro surface area and its provided ES according to the climate models projecting future scenarios?

In detail, the paper is structured as follows: Section 2 presents the study area where Lake Azzurro is located, with the importance of its ES. Section 3 describes the meteorological data, climatological models used for the analysis, the statistical tools applied to data homogenization and trends, and the adopted strategy for the study. Section 4 reports the results obtained using historical temperature and precipitation data in relation to the lake's disappearance and the future projections with the tested methodology. The discussion in Section 5 provides a detailed assessment about impacts on ES, which may be affected by future climate change projections that threaten the lake's water resources; effects that should be considered in adaptation programs, such as sustainability management actions, by policymakers.

2 Materials and methods

2.1 Area of study

Lake Azzurro is a picturesque lake located in the municipality of Campodolcino (Figure 1), a small mountain town in the Valtellina area (Lombardy Region, northern Italy). Situated at an altitude

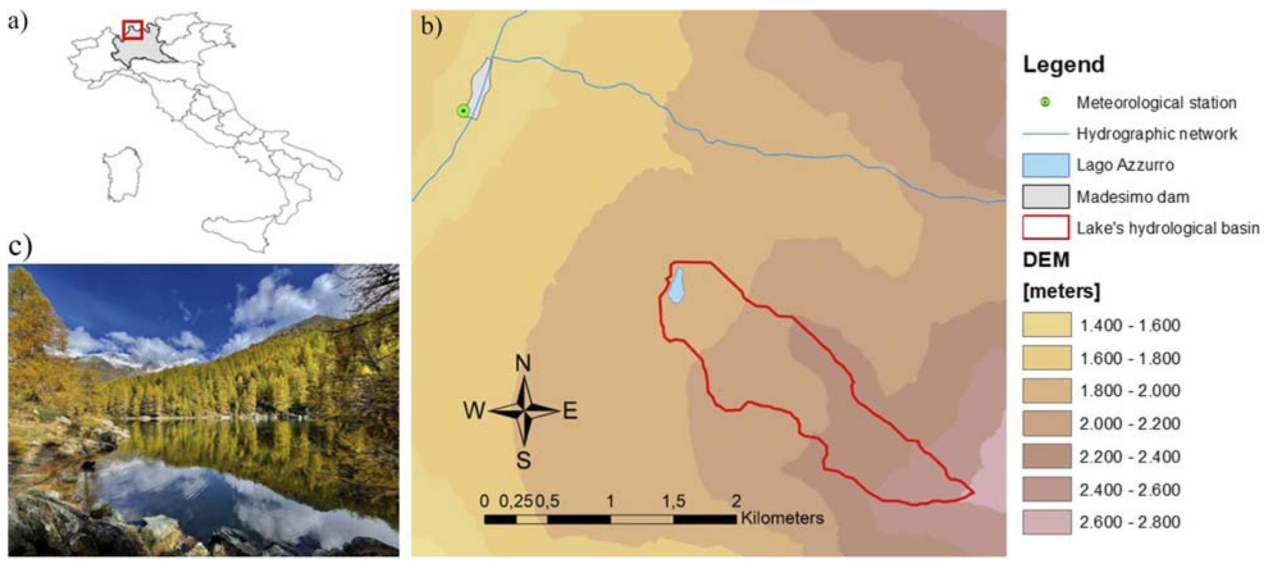

FIGURE 1
Location of Lake Azzurro: the red box placemarks its position in northern Italy **(a)**; a detailed topographic map of the area surrounding the lake **(b)**; an image of the lake, full of water, in October 2023 **(c)**.

of 1,852 m a.s.l., this natural lake has a sub-elliptical surface morphology, an area equal to about 10,750 m^2, with a north–to-south-oriented length of approximately 225 m, a width of about 95 m, and a maximum depth of around 10 m. Its basin (~0.79 km^2) lies within a scenic depression surrounded by larch trees which play a crucial ecological role by providing habitat for a variety of species as well as supporting diverse flora, thereby contributing to both the ecological integrity and cultural value of the lake.

The climate of the region follows a typical alpine regime (Brugnara et al., 2012; Brunetti et al., 2014; Crespi et al., 2017), characterized by long, cold winters with abundant snowfall and temperatures frequently falling below freezing. Due to its geographic location, the valley is exposed to sudden weather variations, including intense rainfall and thunderstorms during the summer months. However, effects of climate change are becoming increasingly evident, as rising temperatures and altered precipitation patterns are beginning to significantly impact the region's ecosystems (Steingruber et al., 2021). In fact, since the early 2000s, a predominant trend has been observed in the frequency of years during which the lake was entirely dried. A collection of old photographs (Figure 2) has provided valuable visual documentation of the lake's recent changing conditions, offering supplementary evidence that supports this research.

On the contrary, information prior to the 2000s are sparse and seldom available to allow a detailed reconstruction of previous lake's conditions.

2.1.1 Lake's ecological importance

To better contextualize the ecological relevance of Lake Azzurro, we listed the ES it provides, according to the CICES classification (Table 1). This framework enables a structured assessment of the lake's contributions to human wellbeing, encompassing provisioning, regulating, and cultural services.

i. The provisioning services of Lake Azzurro extend beyond supplying food for local wildlife. The vegetation surrounding the lake includes medicinal plants and supports traditional practices, such as the use of *Achillea moscata* in herbal infusion. These infusions are traditionally employed to alleviate digestive discomforts, including dyspepsia, abdominal swelling, and flatulence. Additionally, *Achillea moscata* exhibits anti-inflammatory, antimicrobial, and sedative properties, reflecting its ethnobotanical value in local communities (Bottoni et al., 2022).
ii. The lake provides significant regulating services as well, evidenced by its densely wooded landscape, which contributes to mitigating local microclimate fluctuations and sustaining high levels of biodiversity. The rich assemblage of flora and fauna includes species such as *Gentiana verna*, *Campanula cochlearifolia*, and *Achillea moschata*, as well as fauna like *Ichthyosaura alpestris*, roe deer (*Capreolus capreolus*), ibex (*Capra ibex*), and foxes (*Vulpes vulpes*). These species contribute to ecological equilibrium and reinforce the resilience of the ecosystem (Rogora et al., 2018).
iii. In addition to its ecological functions, Lake Azzurro holds substantial cultural value. Its scenic beauty and recreational potential attract visitors for a range of nature-based activities, including hiking, swimming, sunbathing, and picnicking, thereby fostering a deeper experiential relationship with the environment. Lastly, the lake's influence extends into the cultural and artistic realm. Its serene waters and evocative landscape have inspired numerous artists and writers, among them the esteemed Italian poet Giosuè Carducci at the end of the 19th century. Over time, Lake Azzurro has become a source of creative inspiration, leaving a lasting mark on literature and the visual arts.

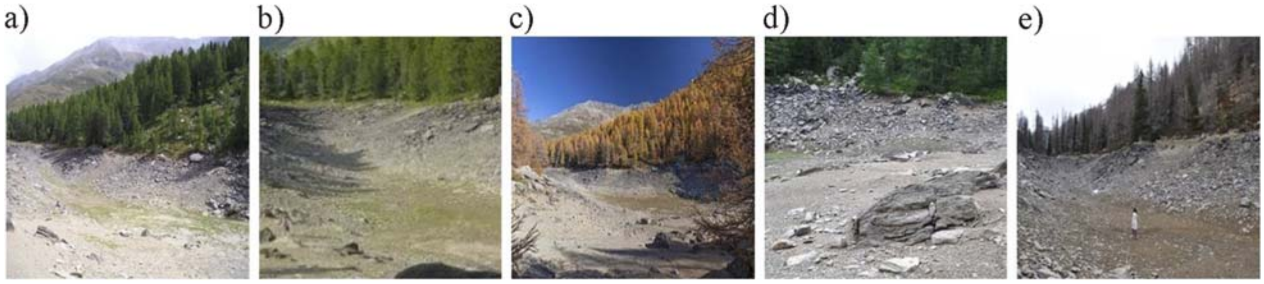

FIGURE 2
Photographic reconstruction of the years with the disappearance of Lake Azzurro: 2005 **(a)**, 2006 **(b)**, 2018 **(c)**, 2022 **(d)**, 2023 **(e)**.

TABLE 1 Summary of ES provided by Lake Azzurro.

Category	Specific ES	Description
Provisioning Services	*Freshwater supply*	Provides surface water essential for alpine wildlife hydration and physiological processes
	Wild plant resources	Presence of medicinal and aromatic plants (e.g., *Achillea moscata*) used in traditional herbal practices, reflecting ethnobotanical value
	Habitat provisioning for fauna	Supports breeding and hydration of alpine fauna, including roe deer, ibex, foxes, and especially amphibians like *Ichthyosaura alpestris*
Regulating and Maintenance Services	*Microclimate regulation*	Dense larch woodlands contribute to temperature moderation and local climate stabilization
	Biodiversity maintenance	High floristic diversity (e.g., *Gentiana verna*, *Campanula cochlearifolia*) supports pollinator activity and overall ecological balance
	Habitat for reproduction and lifecycle completion	Crucial for the reproductive cycle of the Alpine newt and other amphibians that depend on aquatic environments for oviposition and larval development
	Soil stabilization	Vegetation cover, especially mosses and subalpine shrubs, aids in slope stability and erosion control
Cultural Services	*Recreation and ecotourism*	Hiking, swimming, and picnicking around the lake enhance nature-based tourism and promote environmental awareness
	Artistic and inspirational value	The lake's landscape has inspired distinguished literary and artistic works, including poetry by Giosuè Carducci, highlighting its role in cultural heritage and creative expression
	Scientific and educational value	Offers a natural laboratory for studying alpine flora, fauna, and climate-ecosystem interactions, particularly amphibian reproductive ecology

As regards vegetation, the plant life surrounding alpine lakes is uniquely adapted to withstand harsh environmental conditions, including extreme cold, short growing seasons, and nutrient-poor soils. Mosses, lichens, and alpine meadows are commonly found in these environments, with many species exhibiting specialized physiological and morphological adaptations that enable their survival (Körner, 1995). The arboreal vegetation around Lake Azzurro is characterized by relatively low species diversity, largely due to the predominance of *Larix* (larch) trees in the adjacent woodlands (Nascimbene et al., 2006). These flowering plants play a key ecological role by attracting a wide range of pollinators, thereby enhancing local biodiversity, and supporting the broader ecological network (Tu et al., 2024). Additionally, the presence of water serves as a fundamental component for sustaining biodiversity in alpine habitats. Water is essential for the survival and physiological functioning of alpine fauna, supporting hydration, thermoregulation, and key metabolic processes necessary for life at high elevations. Its availability within the lake ecosystem serves as a key attractor for wildlife species (Aublet et al., 2009). Beyond its role as a physical resource, water is also fundamental to the ecological interactions of alpine fauna, supporting critical life processes including reproduction, foraging, and habitat maintenance (De Troyer et al., 2020). In particular, numerous species, especially amphibians, rely on aquatic environments for breeding and oviposition, underscoring the lake's ecological importance as both a habitat and reproductive site; for instance, Lake Azzurro provides optimal conditions for the reproduction of *Ichthyosaura alpestris*, commonly known as the Alpine newt (Mettouris et al., 2017).

2.2 Meteorological data

In this study, we utilized data from the nearest meteorological station operated by the A2A company to reconstruct climatic dynamics. This dataset represents a valuable resource for characterizing the climatic conditions influencing the study area, since these meteorological values provide a high-quality and long-term series of observed meteorological variables, including precipitation (rain and snow) and 2-m air temperature, spanning the period from the 1960s to 2024. The station is situated near the Madesimo dam at an elevation of 1,531 m a.s.l., approximately 1.5 km northwest of Lake Azzurro (Figure 1), and all measurements were daily recorded at 08:00 local time, in compliance with the Italian legislation regulating dam monitoring systems.

2.2.1 Temporal homogeneity check

Before analyzing long-term trends, assessing the homogeneity of climate series is a mandatory step; thus, various homogeneity tests have been developed and are commonly applied to temperature and precipitation records (Brunetti et al., 2012; Caloiero et al., 2011). In this study, we initially employed the Craddock test (Craddock, 1979) to compare the Madesimo series with data from adjacent meteorological stations in Italy and Switzerland. The analysis revealed no significant inhomogeneities in the precipitation series spanning 1967–2024. On the contrary, the temperature series exhibited cold bias during the early period from 1965 to 1980, which was subsequently excluded from further analyses; nevertheless, a sufficient time series remained available for model bias corrections. Once the homogeneity of the series was established, a change-point detection analysis using the Pettitt's test (Pettitt, 1979) was conducted on temperature data for the period 1981–2024. This analysis identified a breakpoint in 2012, which indicates a climatic anomaly, likely attributable to natural variability superimposed on the broader trend of global warming, whereas no breakpoints were found for precipitation.

2.2.2 Statistical tests

Various statistical tests were applied to detect, evaluate, and attribute long-term trends in meteorological data. To determine the significance of these trends over time, the Mann–Kendall (MK) trend test (Mann, 1945; Kendall, 1975) was employed. The MK test identifies monotonic trends, either upward or downward, indicating a consistent increase or decrease in the variable over time, regardless of whether the trend is linear or nonlinear. In this study, a confidence level of 95% was employed for each variable over the respective period where data are homogenized.

To estimate the trend magnitudes, we used the nonparametric method developed by Sen (1968), which calculates the slope by considering all possible pairs of data points. The median of these slopes represents the overall rate of change. The Sen's slope is an alternative to linear regression, robust to outliers, particularly well-suited for detecting non-linear trends too.

2.3 Climate model scenarios

To evaluate future climate scenarios, this study employed the COSMO-CLM Regional Climate Model (RCM), developed by the Climate Limited-area Modelling (CLM) Community and based on the COSMO-LM weather forecasting model. The climate projections used in the analysis consist of two high-resolution dynamically downscaled simulations provided by the CMCC, both driven by the CMCC-CM global climate model.

The first simulation, named *Italy8km-CM* has a spatial resolution of 0.0715° (~8 km) with daily output frequency, covering the entire Italian peninsula. This model has been extensively evaluated (Bucchignani et al., 2016; Zollo et al., 2016), showing good agreement with observational datasets for both mean and extreme temperature and precipitation values. Although it tends to exhibit a general cold and wet bias over the Alps, it has been widely used in various climate impact assessments (Reder et al., 2020; Rianna et al., 2017; Vezzoli et al., 2015).

The second simulation, *VHR-PRO_IT*, was developed within the Highlander project through further downscaling of the Italy8km-CM simulation. It provides a very high spatial resolution of 0.02° (~2.2 km) and it offers hourly output over the Italian territory. While the model configurations between the two simulations are largely consistent, a key physical difference lies in the treatment of convection: in VHR-PRO_IT, only shallow convection is parameterized, while deep convection is explicitly resolved; additional details are provided in Raffa et al. (2023).

The control reference period for the Italy8km-CM simulation spans 1979–2005, with future projections extending from 2006 to 2100 under both RCP 4.5 and RCP 8.5 emission scenarios. For the VHR-PRO_IT simulation, projections cover the period 2006–2070, with a control reference period from 1981 to 2005 under the same scenarios.

As above mentioned, a bias correction procedure was applied to improve absolute values' accuracy of the projections by aligning them more closely with observational data. Since the temperature series is homogenized starting in 1981 and the highest-resolution model data are not available prior to that year, all future projections are bias-corrected using the overlapping period 1981–2005 between the observed and modelled datasets.

2.4 The proposed strategy

The primary output variables extracted from the simulations are precipitation and 2-m air temperature fields, at daily and hourly resolution from the Italy8km-CM and VHR-PRO_IT, respectively. We selected the four closest grid points of the model calculated with the inverse distance weighting technique, as described in Giunta et al., (2017), in order to obtain an average value to be compared with historical data and for future projections.

Since one of the main objectives of this study is to search for a plausible relationship between lake's water presence and climate data, values were examined over the period 1981–2024. As was shown in Figure 2, various drought episodes occurred over the past 2 decades, with 5 years out of 25 with the lake totally parched. Instead, no reliable inferences can be drawn for the previous century, as the region underwent significant transformations of land use, primarily related to tourism development, and ski area enlargements which may have altered water flows within the hydrological basin. Therefore, due to the lack of consistent historical data, our analysis focuses on the current century only.

Adapting a methodology, generally more complex, implemented for flood warning systems to define rainfall thresholds (Martina et al., 2006; Gambini et al., 2023), the proposed approach aims to identify an empirical, rapid, and adaptive threshold between drying periods and climatological variables. To explore this issue, homogenized meteorological data are displayed using a four-quadrant plot, with different combinations of temporal data aggregation to find a separating line between climatic values in relation to periods of lake drying out and water-filled. This work is computed using Support Vector Machine (SVM), a supervised learning method suitable for both classification and regression tasks. SVM aims to find a decision function, typically a line or hyperplane in a higher-dimensional space, which deviates from actual data points by no more than a margin ε; for further details about this tool, see Smola and Scholkopf, 2004; Chang and Lin, 2011, among others.

3 Results

3.1 Climate analysis

Once applied homogeneity and statistical tests, the climate analysis provided clear evidence of a statistically significant rise in temperature (p-value equal to 0.002) over the past 44 years (1981–2024), with an observed increment of approximately 2 °C, corresponding to a rate of 0.4 °C per decade (Figure 3a).

In contrast, precipitation only showed a small increase which is not statistically significant, with p-value equal to 0.179 (Figure 3b); specifically, the data indicated a growth from approximately 1,520 mm in the early ten records to 1,670 mm in the last 10 years, corresponding to an increase of about 37 mm per decade over the period 1968–2024.

Regarding snowfall, Figure 3c illustrated a general tendency that is consistent with observations across the greater alpine region, particularly at mid-altitudes (Matiu et al., 2021). A statistically significant decreasing trend (p-value = 0.02) was observed over the past 60 years, with a change point identified around 1980. It is important to note that the snow data here refers to the hydrological year, which covers the winter seasons, and consists of raw measurements of new snow height (HN), manually collected once every morning. Therefore, some underestimations may occur when compared with data, sub-hourly recorded, from modern automatic snow depth sensors.

3.2 Historical investigation

As shown in Figure 4, three weather data aggregations were considered for a first investigation: Figure 4a, the solar year (January–December), Figure 4b, the meteorological year (December–November), and Figure 4c, the hydrological year (October–September). The years in which the lake completely dried out are highlighted in red, while the others in blue; grey dots refer to those years of the previous century which were discarded in this study.

The preliminary results of the investigation barely identified a clear-cut and direct correlation between climate data and years with or without lake water presence. Therefore, we calculated the precipitation amount during the cold season (November–April) and the mean temperature during the warm season (May–October), each over a 6-month period (Figure 4d); this strategy is more compatible with the lake's natural annual cycle which has a seasonal dynamic. This refined analysis yielded surprisingly distinctive results, clearly separating years when the lake fully dried from those it did not. Furthermore, a theoretical threshold can be identified, and it delineated and classified the two categories. The dashed red line represented, in fact, a classification boundary between two classes computed with the SVM.

3.3 Future projections

To further investigate this issue for the upcoming decades, climate projections were analyzed using two RCP scenarios (4.5 and 8.5), based on simulations from CMCC models in the two distinct grid configurations. This approach aims to enhance the understanding of future dry conditions and their potential implications for Lake Azzurro and the surrounding area, thereby enabling a more comprehensive assessment of challenges the territory may face.

Following the same methodology previously adopted, we considered the average temperature during the 6-month warm season and the total precipitation during the 6-month cold season. The threshold identified in the historical period splits the years in which the lake is expected to dry out completely. To aid interpretation, the graph was divided into four distinct quadrants, each represented by a unique color: blue, red, green, and orange. The blue quadrant corresponds to years with higher winter precipitation and cooler summers, where lake drying events are very unlikely. In contrast, the red quadrant represents years with low winter precipitation and hot summers, conditions under which the lake is very likely to dry out. The green quadrant includes years with warm summers but also high winter precipitation. Finally, the orange quadrant reflects colder and drier years, for which it is more difficult to determine whether the lake dried out or refilled.

In the following plots, the two model simulations (2 km and 8 km) with both the RCP 4.5 and RCP 8.5 are plotted for the 30-year periods: 2041–2070 and 2071–2100 (this latter for the coarser model only).

The findings were striking, showing a clear trend towards drying projected for the next decades, affecting not only the worst-case scenario, but even the more moderate one. Although only minor variability in cold-season precipitation is predicted,

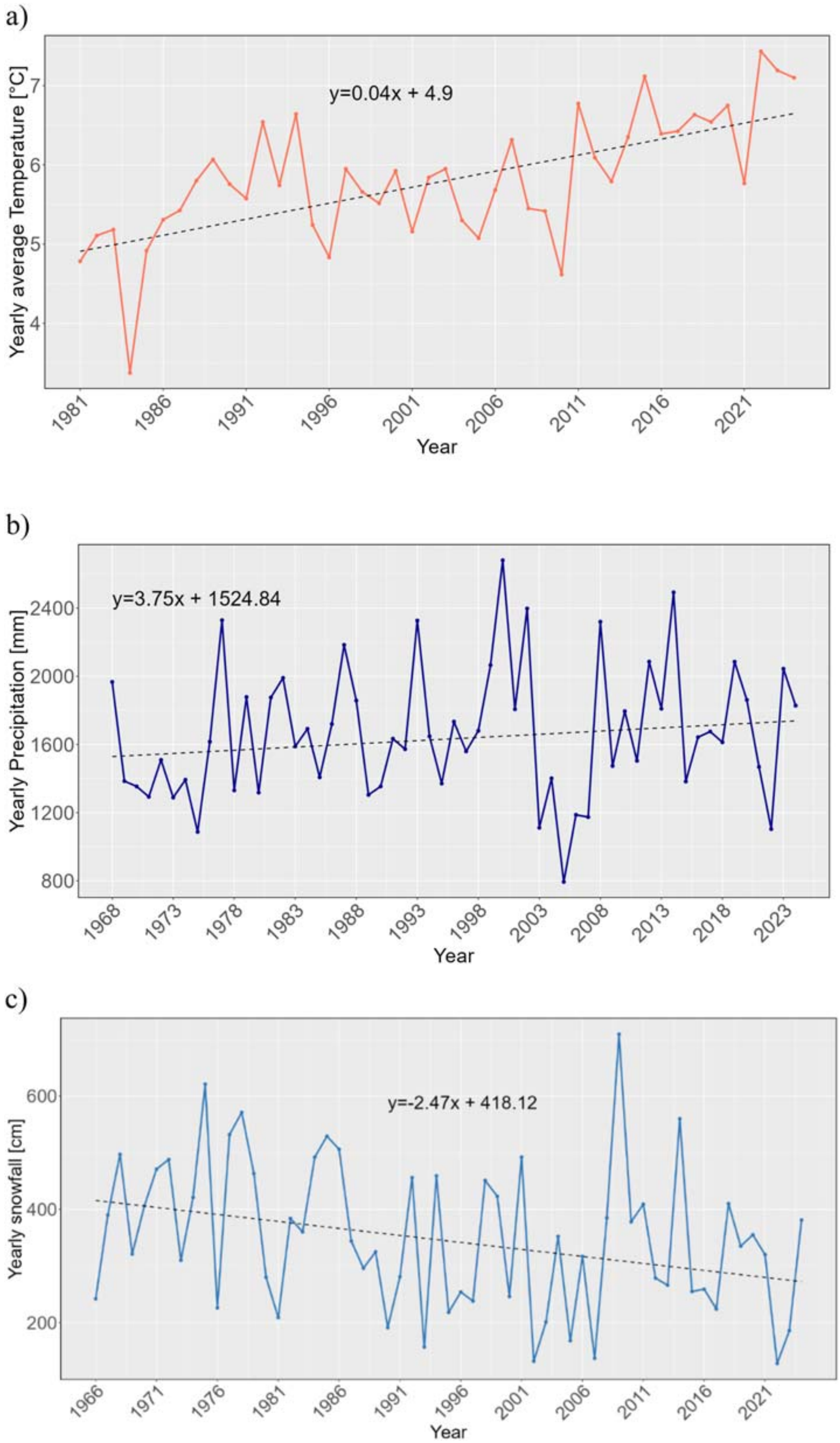

FIGURE 3
Temperature **(a)**, precipitation **(b)** and snowfall **(c)** values over the examined period. Trend slopes are calculated with the Sen's equation.

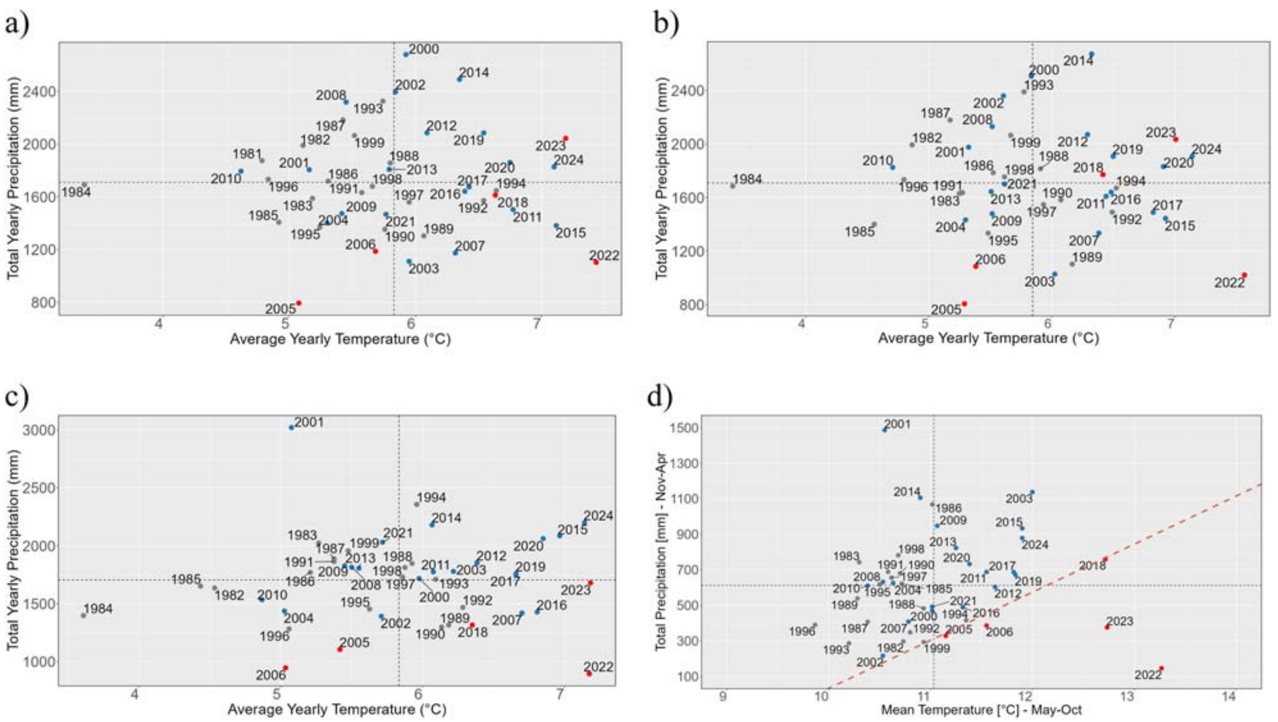

FIGURE 4
Average temperature (on x-axis) and total precipitation (on y-axis) plotted according to the solar **(a)**, meteorological **(b)** and hydrological year **(c)**. The bottom-right **(d)** shows the average temperature and precipitation amounts aggregated at a semestral scale for warm (May–October) and cold (November–April) periods, respectively.

the unprecedented rise in temperatures in the warm season is expected to significantly increase the frequency of lake dry events in the future. In particular, when compared with the observed climatology 1991–2020, the climate projections for Lake Azzurro area, related to the cold semester for precipitation and warm one for temperature, are as follows: under the RCP 4.5 scenario (Figures 5a,c), precipitation is expected to remain relatively stable, with a slight decrease of −2.4% in the 2 km model and −6.1% in the 8 km model for the 2041–2070 period. Meanwhile, temperatures are expected to rise by +2.1 °C and +2.0 °C in the 2 and 8 km models, respectively. For the last 30 years of the century (2071–2100), the 8 km model predicts a temperature increase of +2.7 °C, with precipitation remaining relatively constant at −4.0%.

On the contrary, under the more extreme RCP 8.5 scenario (Figures 5b,d), precipitation is projected to decrease by −6.1% and −4.6% in the 2 and 8 km models, respectively, for the 2041–2070 period. Temperatures, in this case, are expected to rise by +2.8 °C (2 km) and +2.7 °C (8 km). For the period 2071–2100, the 8 km model depicts a huge temperature increase of +5.4 °C, while precipitation is likely to remain stable, showing a slight increase of +1.4%.

Indeed, both simulations led to a clear conclusion regarding the lake's future: a significantly increased frequency of complete drying events in the coming decades. Specifically, between 2041 and 2070, simulations estimated 24 and 23 potential drying cases with the 2 and 8 km models, respectively, under the RCP 4.5 scenario, and 27 and 25 events under the RCP 8.5 scenario. By the end of the century, the 8 km model has no recourse: the combination of significantly higher temperatures, with consequently increased evaporation rates, will lead to the complete disappearance of the lake.

4 Discussion

In the last 2 decades, the more frequent disappearance of Lake Azzurro has underscored the urgency of addressing environmental challenges in alpine regions, such as rising of water surface temperature, decreasing of the oxygen levels in lakes (Dresti et al., 2023), and loss of habitat for macroinvertebrates and fish highlighting their sensitivity to climate change impacts (Boggero et al., 2023). These changes directly compromise several ES, including freshwater and habitat provision, microclimate regulation, and recreational and cultural opportunities. The reduction of these services can have tangible consequences for local communities, impacting water availability for domestic use, tourism, and traditional practices, influencing the broader region by altering hydrological connectivity and nutrient cycling as well. Moreover, the ecological disruptions significantly affect flora and fauna: elevated temperatures and lower oxygen concentrations can reduce survival and reproduction of sensitive species, such as alpine newts, trout, and other aquatic organisms, while the loss of vegetative cover may further compromise soil stabilization and biodiversity. Overall, global warming threatens both the ecological integrity of Lake Azzurro and the human communities that depend on its services, highlighting the critical need for monitoring and adaptive management strategies. Projections based on future climate

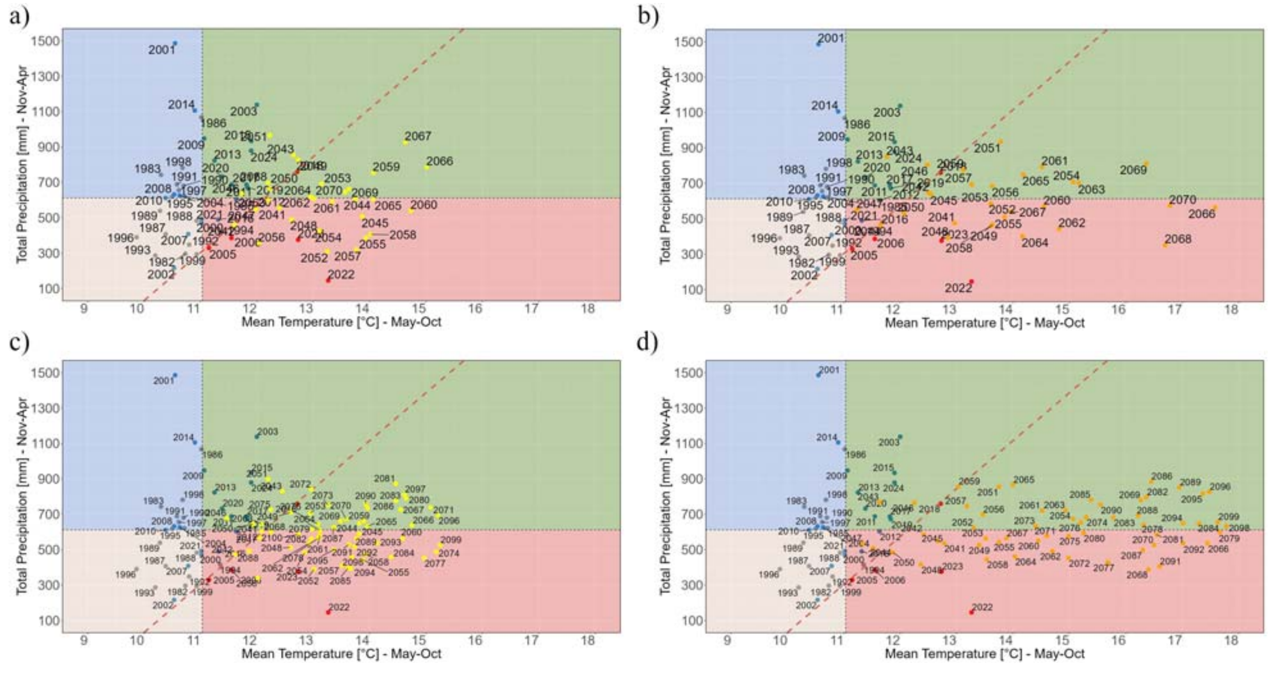

FIGURE 5
Historical data and future projections under the RCP 4.5 **(a, c)** and 8.5 **(b, d)** scenario with the 2 km **(a, b)** and 8 km models **(c, d)**.

scenarios depicted a stark and alarming picture: rising temperatures are expected to exacerbate the lake's vulnerability. The accelerated melting of glaciers (Zemp et al., 2006) and reduced snow cover that feed the lake may lead to prolonged drought events. These changes could further destabilize the lake's hydrology, ultimately resulting in its disappearance.

A previous study by Mariani et al. (2011) investigated Lake Azzurro's geology and geomorphology, focusing on the mechanisms underlying its cyclical water level fluctuations; however, few hydro-meteorological observations in this area were available as model input. In this study, we adopted an alternative approach by combining temperature and precipitation values at different temporal scales to identify reliable relationships between cold, warm, dry, wet years and the lake's disappearance. This analysis, supported by visual records, has been instrumental in illustrating the lake's dynamics and enhancing the interpretation of historical climate data. The availability of long and continuous weather observations from the A2A monitoring site, once homogenized, has further improved the accuracy of our analysis and deepened our understanding of local climate patterns and trends. Although the recent slight increase in precipitation values (Figure 3b) might appear reassuring, it should be viewed with caution. The absence of significant precipitation changes does not mitigate the urgency of addressing the marked rise in temperature (Figure 3a). As demonstrated, these two climatic factors are closely interconnected with the lake's persistence, and their interaction is critical for developing effective adaptation strategies.

Historical climate analysis has revealed a clear relationship between the lake's drying and warmer-drier periods, with the phenomenon becoming increasingly pronounced in recent decades. For instance, the year 2022, documented as the hottest year on record in the region (Figures 3a, 4) by the time this paper was written, was particularly remarkable in this respect, with a record-breaking drought in the entire Po River basin during that summer period (Montanari et al., 2023).

Future trends are even worse (IPCC, 2021). High-resolution climate projections under different scenarios, RCP 4.5 and RCP 8.5, are, in fact, taken into account. RCP 4.5 represents a moderate scenario, where greenhouse gas emissions increase initially but stabilize in the second half of the 21st century. This pathway assumes the implementation of global climate policies, technological advancements, and improvements in energy efficiency, resulting in declining emissions after 2040 (Thomson et al., 2011). This is considered a plausible future trajectory, characterized by moderate mitigation efforts that are nonetheless insufficient to avoid substantial climate change impacts. RCP 8.5, often referred to as the "business-as-usual" scenario, assumes continued increases in greenhouse gas emissions with no significant mitigation policies. Although considered less likely today due to evolving climate policies, it remains a useful worst-case scenario for exploring the consequences of unchecked emissions and severe climate change (Knutti et al., 2016). The model results predicted a dramatic outcome, indicating a higher frequency of years with complete drying in the 2041–2070 climatological period according to projections from both CMCC models. Conditions are projected to worsen further by the end of the century, with temperature increases during the warm season reaching up to 5 °C. Combined with higher evaporation rates, this is expected to lead to the complete disappearance of the lake which will no longer provide ES. Therefore, its future depends on addressing this accelerating drying trend that requires careful consideration of actions to take, including sustainable conservation strategies, climate change adaptation, and integrated resource management.

The findings from Lake Azzurro align with evidence reported for other alpine lakes that have been the focus of ES assessments and climate impact studies (Tiberti et al., 2020; Tom et al., 2022). These studies demonstrate that small high-altitude lakes play a crucial role in freshwater provision, biodiversity support, and amphibian reproduction, while being highly sensitive to hydrological fluctuations driven by climate change as well. Long-term monitoring in the Central Alps (e.g., Swiss Engadine and Austrian Tyrol) has documented shifts in species composition, altered thermal regimes, and increasing stress on cultural and recreational services (Schirpke et al., 2021). Beyond the Alpine region, similar climate-driven dynamics have been observed worldwide, such as in Lake Poopó in Bolivia (Satgè et al., 2017; Perreault, 2020), Lake Waiau in Hawaii (Patrick and KauahiKaua, 2015), and Lago di Pilato (Padula et al., 2021) in the Central Apennines (Italy). These examples highlight the vulnerability of small, climatically sensitive lakes to shared drivers, including rising temperatures, reduced snowpack and earlier melt, intensified drought and evapotranspiration, and altered hydrological connectivity, underscoring the unique ecological and cultural values that characterize each site as well. Positioning Lake Azzurro within both the alpine and global contexts emphasizes the need for integrated, multi-scalar approaches to ES monitoring, and illustrates how local ecological changes mirror broader systemic processes.

4.1 Impacts on ecosystem services

Due to the intensifying impacts of climate change and the projected increase in the frequency, intensity, and duration of seasonal lake disappearance events under high-resolution climate scenarios, Lake Azzurro is expected to experience substantial transformations. These changes are likely to have profound consequences, not only for the physical and ecological integrity of the lake system itself, but also for the broader socio-ecological landscape in which it is embedded. The most immediate and tangible ecological repercussions are anticipated to affect the native vegetation and fauna, as described in Section 2.1.1, whose life cycles, distribution, and survival are intimately linked to the persistence of the lake's hydrological regime (Parker et al., 2008).

The decrease or complete loss of aquatic habitat would result in a cascade of biological disruptions, including a reduction in species richness, a reorganization of community composition, and a potential collapse of key functional groups (Murphy and Romanuk, 2014). Biodiversity loss is likely to be especially pronounced among specialized taxa with narrow ecological niches and limited dispersal capacity. One such example is the alpine newt, a species that critically depends on stable aquatic environments for reproduction (Thuiller et al., 2005b; Bernabò et al., 2023). The progressive decline of suitable breeding conditions could lead to reproductive failure, population fragmentation, and, ultimately, local extinction, particularly in the absence of alternative habitats that meet the species' specific ecological requirements. Alpine and glacial aquatic habitats, that suffer drying or disappearance, often exhibit sharp decreases in biodiversity and functional diversity (Slemmons et al., 2013). A parallel can be drawn with alpine pond systems in the French Alps, where accelerated drying rates, not just warming, have been shown to severely compromise species occupancy and connectivity, underscoring the susceptibility of specialized fauna to hydrological disruptions (Lamouille-Hébert et al., 2025). Macroinvertebrates, which serve as vital indicators of freshwater ecosystem health and contribute to nutrient cycling, food web dynamics and water purification processes, are similarly vulnerable; their limited thermal tolerance and dependence on stable hydrological regimes make them highly susceptible to climate-driven shifts in temperature, flow patterns, and water availability (Mantyka-Pringle et al., 2014; Besacier Monbertrand et al., 2019). These organisms typically exhibit limited mobility and high-site fidelity, rendering them particularly susceptible to abrupt habitat loss. In case of complete lake drying, macroinvertebrate communities would be forced either to relocate to marginal or ephemeral aquatic habitats, often characterized by suboptimal ecological conditions (Boulton and Lake, 1992; Williams, 2006), or to undergo dramatic population declines (Boulton, 2003). The latter scenario could severely disrupt trophic interactions and diminish the resilience of the ecosystem to future disturbances (Palmer and Ruhi, 2019).

The disappearance of mountain lakes, like Lake Azzurro, could entail profound ecological and socio-economic repercussions. Locally, the loss of freshwater resources may compromise drinking water availability and downstream hydrological regulation (Viviroli et al., 2007; Huss et al., 2017). At the same time, the decline in recreational and cultural ES would undermine ecotourism, an important source of income and identity for mountain communities (Rewitzer et al., 2017; Steiger et al., 2022). Ecologically, the reduction of habitat essential for species reproduction, particularly amphibians and cold-water fish, would threaten biodiversity and destabilize ecosystem balance, with cascading impacts on food webs and local livelihoods (Jacobsen et al., 2012). Taken together, these findings highlighted the intertwined vulnerability of natural and human systems in alpine environments and stress the urgency of integrated climate adaptation strategies.

Even in hydrologically favorable years when the lake remains partially or fully intact, increasing air temperatures, driven by broader climate warming trends, are projected to exert indirect but significant stress on the aquatic system. Elevated air temperatures contribute to corresponding rises in water temperature, which can shift the thermal regime of the lake beyond the physiological tolerance thresholds of cold-adapted aquatic species (Wetzel, 2001). These changes may facilitate the establishment of thermophilic organisms, including non-native or invasive species, further altering their assemblages and competitive dynamics (Kraemer et al., 2021). Moreover, warmer water conditions may promote the proliferation of cyanobacteria and other potentially harmful algal species, potentially leading to the occurrence of algal blooms which can deteriorate water quality, produce toxins, deplete oxygen levels, and cause significant harm to aquatic life (Foley et al., 2012). This is a well-known phenomenon occurring in many lakes around the world (see as an example Salmaso et al., 2016; Pritsch et al., 2023).

Beyond ecological impacts, the disappearance of Lake Azzurro would entail considerable losses in terms of cultural ES as well. The lake represents a key element of the region's natural heritage for residents and visitors. Local communities have long relied on the lake's surrounding flora for medicinal purposes, with traditional knowledge passed down through generations. Medicinal plants such as *Achillea millefolium* have been integral to local folk medicine. These plants are not only valued for their therapeutic properties, but also for their cultural significance, serving as cultural keystone species that embody the deep connection between people and their environment. The loss of Lake Azzurro would thus mean the erosion of this rich cultural heritage, diminishing the sense of identity and continuity for the local population. Furthermore, the degradation or disappearance of the lake could lead to a decline in ecotourism, accompanied by a weakening of its appeal and sightseer engagement, which are largely based on nature-based recreation.

A public survey was conducted by the authors of this study to gather qualitative insights into local perceptions of the lake's disappearance, its cultural significance, and the historical variability of its hydrological regime. The unexpected level of interest and participation, with more than 500 responses, clearly demonstrated the community's strong connection to Lake Azzurro. It underscored the significance of this alpine lake and its environment to the residents. The answers provided a comprehensive understanding of the ES associated with Lake Azzurro and offer valuable knowledge for future conservation and management efforts that not only contribute to expanding attractiveness about the ES provided by the lake but also serve to build awareness among the public about the lake's importance. The community's active involvement highlighted the desire to have their voices heard and to actively participate in the preservation of their natural surroundings.

4.2 Sustainable management policies

Preserving and sustainably managing Lake Azzurro is therefore essential to maintaining environmental balance, safeguarding the ES the lake provides, and improving the quality of life for present and future generations. Efforts should be concentrated on enhancing the lake's resilience through ecosystem-based adaptation strategies (Endter-Wada et al., 2020). In this context, coordinated action among scientists, policymakers, and local stakeholders to implement measures such as sustainable water management and enhanced ecological connectivity is fundamental for effective adaptation to climate change. Sustainable water management encompasses strategies and practices that ensure the availability and quality of water resources for both human and ecological needs, balancing consumption with replenishment, and integrating ecosystem requirements into water governance frameworks (Brown, 2005; Makanda et al., 2022). Enhanced ecological connectivity refers to the maintenance or restoration of landscape elements that facilitate the movement of species and ecological processes across fragmented habitats, thereby increasing resilience to environmental changes and enabling species migration in response to shifting climate conditions (Krosby et al., 2010).

Concrete examples from other mountain lake contexts can further illustrate feasible pathways for Lake Azzurro. For instance, in the Pyrenean high-altitude lakes, small-scale hydrological interventions (e.g., seasonal water retention ponds, Sentenac et al., 2025) have been tested to buffer extreme fluctuations in water availability. In Swiss Alpine catchments, riparian vegetation restoration has been shown to stabilize soils, improve water quality, and moderate local microclimates (Tisserant et al., 2020). Amphibian conservation programs in Italy (see, for example, Bombi et al., 2011) have successfully established artificial breeding ponds and introduced access restrictions during the reproductive season to support sensitive populations. Continuous ecological monitoring and adaptive management should be central to maintaining habitat quality, supporting species persistence, and safeguarding the long-term functionality of ES.

To confront escalating risks and safeguard the invaluable services provided by Lake Azzurro, immediate and coordinated actions are imperative. Educational campaigns and outreach initiatives should cultivate a sense of responsibility and encourage behavioral changes that support the preservation of this unique ecosystem. Furthermore, the implementation of sustainable tourism practices and didactic initiatives will enhance awareness and appreciation of Lake Azzurro's ecological significance. As an example of such initiatives, in Alberta (Canada) national parks like the Jasper and Banff, have adopted eco-friendly tourism practices, such as reducing single-use plastics, utilizing alternative energy sources, and implementing wildlife conservation programs (Notzke, 2004). In the Bolsena Lake area (Central Italy), the "Knowing Lake Bolsena" educational program (https://www.bolsenalagodeuropa.net/en accessed on 1 August 2025) has been instrumental in raising environmental awareness among local students. Initiated in the 1990s, this program offered training for teachers and hands-on activities for middle school students, focusing on the lake's ecosystem, water quality, and sustainable practices. The program's success highlighted the importance of integrating environmental education into school curricula. Such measures could foster environmental stewardship among both residents and visitors, thereby supporting the long-term preservation of this invaluable natural resource. Without sustainable management policies, the impacts of climate change on Lake Azzurro will become increasingly pronounced.

4.3 Strengths and limits of the study

This study has adopted a pragmatic approach to analyze effects of climate change on Lake Azzurro. The proposed method can be applied and replicated over other alpine small lakes which exhibit the same or similar seasonal dynamics. The interconnection between past climate and lake water levels shows a reasonable outcome which can be adopted as a simple and practical method to predict the lake presence in future climatic scenarios. In fact, the evidence presented throughout this work unequivocally pointed out a troubling future scenario: the potential disappearance of the lake itself. The inclusion of climate model allowed for an assessment of the region's future climatic conditions, thereby enabling it to predict potential lake drying out frequency.

The approach adopted in this study has certainly some limitations. Although the relationship between climate data and periods of recharge and discharge of the lake basin indicated a clear correlation, further investigations using hydrological models would be valuable to better quantify the delicate hydrological equilibrium in mountainous areas at a finer temporal scale (Boscarello et al., 2014; Ravazzani et al., 2016). Particularly for snow dynamics, the reducing snowfall and rapid rise in temperatures may alter and imbalance the current lake's variations, which are not stationarity, by the end of this century. This study, for instance, did not account for the precise timing of the lake's complete disappearance during the warm season; instead, a year was classified as dry, if the threshold was exceeded. For example, in 2023, the lake remained empty until the end of August but refilled in the following 2 months due to extraordinary precipitation that occurred on that autumn.

Furthermore, historical data on the lake's water levels prior to the year 2000 are limited and coarse. Therefore, we focused our analysis on the last 25 years, for which territorial data were available to establish a clearer relationship between climate data and drying events. Lastly, in this paper, it was not possible to calculate quantitative indices and provide a measure and evaluation of the targeted ES, as there were no direct measures on the lake physical, chemical or biological features.

ES assessment has, in fact, proven to be a useful tool to enhance the value of natural areas, clarify their functions and contributions, and support the development of mitigation activities and policy incentives. However, this study primarily focused on climate projections and their potential impact on the drying cycle of the lake; assessing ES was not the main objective. Nevertheless, future studies could complement this work, by quantifying ES through satellite and LiDAR data, as well as on-site measurements and instrumentation. Freshwater provision could be assessed through seasonal water volumes and basic water quality parameters (e.g., pH, conductivity, dissolved oxygen), while wild plant resources could be monitored through species richness and biomass of medicinal plants. Habitat provisioning for fauna may be quantified via amphibian breeding success rates or camera-trap counts of key alpine mammals. Regulating services could be captured through canopy cover and local temperature buffering (microclimate regulation), species diversity indices for biodiversity maintenance, larval survival rates of amphibians for reproductive habitat, and vegetation cover or soil erosion rates for soil stabilization. Lastly, cultural services could be tracked using visitor counters, expenditure data, frequency of artistic references, or the number of scientific publications and educational visits related to the lake. These indicators provide a basis for future monitoring programs and could substantially enhance the robustness and comparability of ES evaluations in alpine environments.

5 Conclusion

Global warming has accelerated environmental vulnerability in most natural ecosystems, including alpine lakes such as Lake Azzurro in the Val Chiavenna area of the Italian central Alps. Fed primarily by precipitation in the cold season, this lake has a delicate hydrological balance. Like glaciers, lakes' survival depends on temperatures during the warm season, which affects evaporation rates. In this study, we first conducted a climate analysis using historical local meteorological data to investigate the relationship between climate variables and Lake Azzurro's disappearance over the past 6 decades. A clear connection was found by plotting the average temperature of the warm season (May–October) and total precipitation during the cold season (November–April) with a threshold traced as frontier to separate years with no water in the lake.

In the last 25 years, the data revealed an alarming trend of rising temperatures and reduced snowfall in the region, accompanied by slight changes in precipitation patterns. These shifts have already begun to place considerable stress on Lake Azzurro, contributing to declining water recharge and altering hydrological dynamics. Subsequently, to better understand future lake trends, we analyzed climate projections for the coming decades using two RCP scenarios (4.5 and 8.5), based on simulations from CMCC climate models at two spatial resolutions (2 and 8 km). The results indicate the complete disappearance of the lake by the end of the century. While precipitation is projected to remain relatively stable, the substantial increase in temperature, rising by 2 °C–3 °C by 2070 and up to 5 °C by 2100 under the worst-case scenario (RCP 8.5), will likely lead to the lake's total desiccation. Therefore, urgent and decisive actions are essential to mitigate the risks posed by climate change and to ensure the long-term survival of this unique ecosystem.

The potential loss of the lake and its associated ecosystem functions would have, in fact, profound consequences, disrupting the delicate ecological balance of the surrounding environment. It would also deprive local communities and future generations of critical benefits, including clean water, habitat provision, climate regulation, and recreational opportunities. Therefore, the future of Lake Azzurro hangs in balance, demanding immediate strategies and a strong commitment to climate change mitigation. Sustainable policies must be implemented to preserve the lake's nature and ensure its continued existence. Only through concerted and long-term efforts, Lake Azzurro and its ES can be safeguarded, leaving a legacy of ecological integrity and resilience for generations to come.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AC: Writing – review and editing, Formal Analysis, Writing – original draft, Methodology, Investigation, Validation, Supervision, Data curation, Visualization, Conceptualization. GT: Writing – original draft, Investigation, Data curation, Conceptualization, Formal Analysis, Visualization. EG: Software, Visualization, Data curation, Formal Analysis, Writing – review and editing. MM: Writing – original draft, Formal Analysis, Visualization, Data curation, Conceptualization, Supervision. GB: Supervision, Conceptualization, Writing – original draft, Project administration, Visualization. CD: Writing – original draft, Investigation, Writing – review and editing, Methodology, Data curation, Visualization, Validation, Formal Analysis, Conceptualization, Supervision.

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Conflict of interest

Author MM was employed by Montana S.p.A.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer AW declared a past co-authorship with the author AC to the handling editor.

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