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# The old and the new on threats to high-mountain lakes in the Alps: A comprehensive examination with future research directions

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ABSTRACT

The high-mountain lakes of the Alps, perched like glistening gems in the cradle of Europe's most formidable mountain range, have for generations epitomized nature's majesty. These remote and pristine bodies of water have served as invaluable sentinels of global change, repositories of geological history, and sources of freshwater for the surrounding regions. Yet, despite their seemingly imperturbable beauty and seclusion, these high-mountain lakes are not immune to the evolving forces of our changing world. Re-emerging threats, exacerbated by the relentless march of climate change and intensified human activities, cast a shadow over their future, posing profound challenges that demand our attention. The aim of this perspective is to shed light on the main emerging threats, raise awareness, and advocate for proactive actions aimed at preserving and protecting high-mountain lakes. These threats include climate change, retreat of glaciers, UV radiation, long-range transport of contaminants, impact of alien species and water usage for Alpine storage power stations. Additionally, increased tourism and recreational activities in these pristine environments can cause habitat disturbance, further endangering these unique ecosystems. The present perspective article also offers valuable perspectives on the necessity of monitoring and research efforts in high-mountain lakes. Such actions are crucial for comprehending the ecological well-being of these ecosystems, evaluating the consequences of environmental shifts, and devising successful conservation strategies.

## 1. Introduction

High-mountain lakes can be found in a variety of climatic zones, including temperate and tropical regions (Pastorino and Prearo, 2020). These lakes are typically located at high altitudes in mountainous areas, and their presence is often determined by factors such as elevation, topography, and climate. Temperate high-mountain lakes are commonly found in mountain ranges in regions with temperate climates, such as the Rockies in North America, the Alps in Europe, and the Himalayas in Asia. These lakes are usually situated at higher elevations, often above the tree line (Catalán et al., 2006; 2009). They may be glacial lakes, formed by the melting of glaciers, or cirque lakes, which occupy basins carved by glacial activity (Catalán et al., 2006). On the other hand, tropical high-mountain lakes can be found in mountainous areas within tropical regions, like the Andes in South America or the East African Rift mountains (Jacobsen, 2008). Despite the warm and humid lowland tropical climates, the high elevations of these regions can support the existence of cooler, Alpine-like environments. Tropical high-mountain lakes may also be associated with volcanic activity, as some are formed in volcanic calderas (Mosquera et al., 2022). These lakes can be ecologically distinct from their temperate counterparts, with unique flora and fauna adapted to the tropical environment. Indeed, they act as reservoirs of biodiversity, serving as vital habitats for a range of organisms (Nevalainen et al., 2015; Cuna et al., 2022).

High-mountain lakes, situated in the remote, pristine regions of the world's highest peaks, serve as invaluable indicators of global change (Moser et al., 2019). These high-altitude aquatic ecosystems, often considered the sentinels of environmental changes, offer profound insights into the effects of climate change, pollution, and human activity on a planetary scale (Moser et al., 2019; Pastorino and Prearo, 2020).

While high-mountain lakes in tropical regions also encounter challenges, those located in the Alps, nestled within the pristine and majestic

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landscapes of the Alps, face a confluence of environmental pressures that jeopardize their fragile ecosystems (Pastorino and Prearo, 2020). Schirpke and Ebner (2022) conducted a study that explored the vulnerability of small, natural high-mountain lakes (n = 2,455) in the European Alps to the various pressures associated with global change. The findings revealed that over half of the lakes were significantly exposed to global change pressures (Schirpke and Ebner, 2022). High-mountain lakes in the Alps face a variety of threats, some of which may be re-emerging or evolving due to environmental changes and human activities. Here are some potential (re)emerging threats to high-mountain lakes in the Alps: climate change, glacial retrait, increased exposure to ultraviolet (UV) radiation, long range transport of contaminants, introduction of alien species, water usage for Alpine storage power stations and recreational activities (i.e., tourism) (Fig. 1).

Global climate change, manifested in rising temperatures, is one of the foremost perils. The warming climate triggers earlier snowmelt, disrupts natural hydrological patterns, and hastens the shrinkage of glaciers that are vital sources of water for these lakes (Pepin et al., 2022). Consequently, shifts in the timing and quantity of water inflow impact the overall health of these remote ecosystems.

Another peril emanating from climate change is the increased exposure to ultraviolet (UV) radiation (Barnes et al., 2019). High-mountain lakes, located at lofty altitudes and under the thin Alpine atmosphere, receive amplified doses of UV radiation, posing risks to the aquatic organisms dwelling within (Durán-Romero et al., 2020).

Long-range transport of contaminants (i.e., heavy metals, persistent organic pollutants and microplastics) and acid deposition (i.e., sulfur and nitrogen oxides) are yet another significant concerns (Catalán, 2015; Pastorino et al., 2022a). These contaminants can lead to water quality deterioration, negatively affecting the aquatic life and compromising the ecological integrity of these habitats (Catalán, 2015).

Alien species represent a growing menace to high-mountain lakes (Ventura et al., 2017). Both non-native flora and fauna can be inadvertently introduced, and once established, they often outcompete native species, leading to ecological imbalances and further destabilization of these ecosystems (Schindler and Parker, 2002; Bonelli et al., 2017).

Finally, recreational activities in these pristine areas also pose threats (Schirpke et al., 2021a). Tourism can lead to trampling of fragile lake shorelines, littering, and disturbance to local wildlife, all of which can degrade the lakes' surroundings.

In essence, high-mountain lakes in the Alps confront a multitude of emerging threats, requiring immediate and sustained efforts in awareness and research to safeguard these vital components of our natural heritage. The main aim of perspective is to illustrate the aforementioned emerging threats, increase consciousness, and promote proactive initiatives and research for the preservation and safeguarding of high-mountain lakes located in the Alps. This endeavor is geared toward researchers, policymakers, and conservationists, emphasizing the importance of taking action to protect these key ecosystems.

## 2. Diversity and characteristics of high-mountain lakes in the Alps

The Alps, Europe's premier mountain range, are renowned for their stunning landscapes and diverse ecosystems (Fischer et al., 2008). The sheer number of high-mountain lakes in the Alps is a testament to the geological forces that have shaped this region over millennia. While pinpointing an exact count of these lakes is a challenging endeavor due to their vast and often remote distribution, experts estimate that there are over 2,000 high-mountain lakes throughout the Alps (Schirpke and Ebner, 2022). This number may vary depending on the criteria used to define a high-mountain lake and the precise geographic boundaries of the Alps. Nevertheless, it is evident that these lakes are integral to the Alpine environment, contributing to its ecological diversity and serving as vital indicators of environmental change.

The Alpine region spans several countries, including France, Italy, Switzerland, Austria, Germany, and Slovenia, among others. High-mountain lakes can be found in all these countries, nestled within various parts of the mountain range. Their distribution is not uniform,

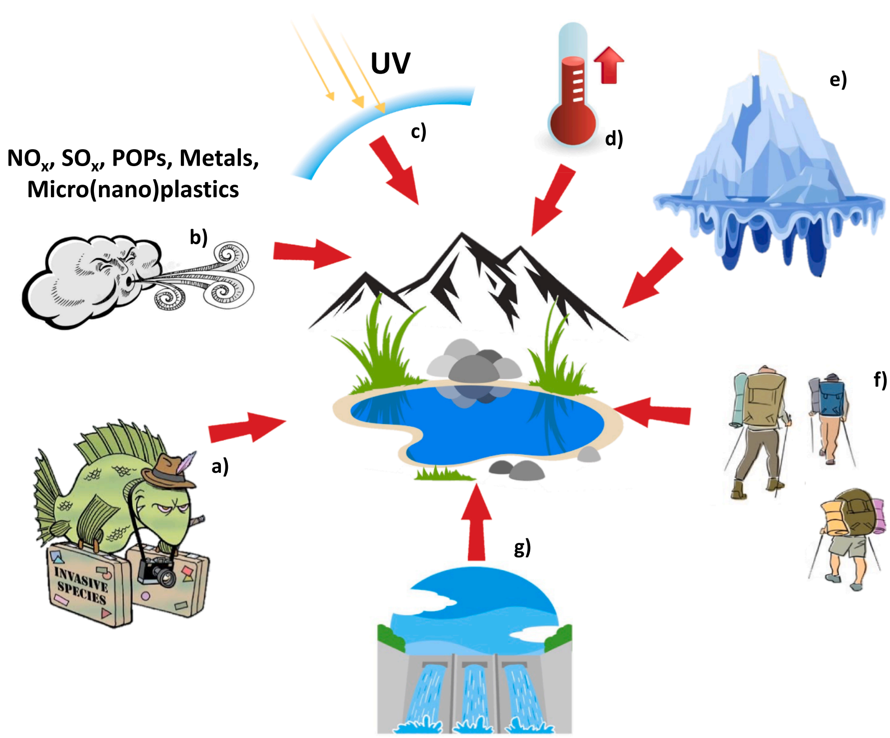


Fig. 1. Emerging threats to high-mountain lakes located in the Alps: a) alien species; b) long-range transport of contaminants; c) UV radiation; d) climate change; e) glacial retreat; f) recreational activities; g) hydropower facilities.

with some areas boasting more lakes than others. The Eastern Alps, for instance, are home to a substantial number of high-mountain lakes, thanks to their diverse topography and abundant precipitation. Meanwhile, the Western Alps, with their dramatic landscapes, are equally renowned for their high-mountain lakes, albeit with variations in numbers and altitudes. These lakes are not confined to a single elevation; rather, they can be found above the tree line at various altitudes, ranging from about 1,500 m (4,921 feet) above sea level (a.s.l.) to well over 2,500 m a.s.l. (6,561 feet) or even higher (Catalán et al., 2006).

High-mountain lakes come in a wide array of sizes and shapes, from expansive bodies of water to small, crystal-clear tarns. Some are situated in basins gouged out by ancient glaciers, while others occupy depressions formed by geological processes (Catalán et al., 2006; 2009). Their origins are as diverse as their appearances, with glacial meltwater being a common source. These high-mountain lakes are more than just picturesque features of the landscape; they are essential components of the Alpine ecosystem. They support a variety of flora and fauna, serving as habitats for numerous species adapted to high-altitude life (Cantonati et al., 2021; Pastorino et al., 2022b). Amphibians, and various invertebrates inhabit their waters, while Alpine plants flourish along their shores (Ventura et al., 2017). Generally, they are fishless, but fish (mainly *Salmo trutta* and *Salvelinus fontinalis*) were introduced in several lakes for fishing purpose (Tiberti et al., 2014; Pastorino et al., 2019a). The biodiversity within and around these lakes reflects the adaptability and resilience of life in extreme environments (Pastorino et al., 2019b).

## 3. Emerging threats to high-mountain lakes from Alps

### 3.1. Climate Change

Rapid changes in the climate have been recorded on a global scale since the beginning of the industrial era (Abbass et al., 2022). These shifts are marked by rising temperatures, alterations in precipitation trends, and a heightened occurrence and severity of extreme weather events such as heatwaves and droughts (Ali et al., 2023). These events not only pose direct threats to biodiversity but also impact the livelihoods of communities residing in these high-altitude regions (Ali et al., 2023; Schlingmann et al., 2021).

Climate change in the Alpine region is a pressing issue that threatens the delicate balance of this breathtakingly beautiful and ecologically diverse area (Pieratti et al., 2020). In the European Alps, during the 20th century, temperatures increased by +2 °C (CREA, 2023). The pace of this warming, which has been observed since the start of the Industrial Revolution, accelerated from the 1980s onward, reaching a rate of +0.5 °C per decade (CREA, 2023). In terms of temperature conditions, a 0.5 °C change corresponds to roughly a 100-meter (about 328 feet) shift in elevation. This means that for species to remain in the same temperature conditions, they would need to move 100 m uphill (CREA, 2023). Warming is particularly pronounced in mountain environments because rising temperatures result in a reduction in the areas covered by ice and snow, which normally reflect the sun's rays (Rangwala and Miller, 2012).

While global precipitation patterns have remained relatively stable throughout the 20th century, there have been noticeable regional and seasonal shifts (Pepin et al., 2022). Since 1960, winter precipitation has notably decreased in southern France, while an increase has been observed in the north (CREA, 2023). In the Alps, which are situated at the convergence of Mediterranean and Atlantic weather systems, these variations are highly localized. For example, a more pronounced reduction in summer precipitation is noticeable in the southern part of the French Alps (CREA, 2023).

Warming temperatures are also altering the Alpine ecosystem. The ecological response to temperature increase is contingent on the characteristics of individual species (Viterbi et al., 2020). Such responses may lead to alterations in species interactions, occurring either within the same trophic level or between different trophic levels, ultimately resulting in broader changes in ecological communities (Rogora et al., 2018). The observed and anticipated effects of global warming on wildlife are predominantly manifested in alterations in physiology, timing of natural events (phenology), and the geographical distribution of species (Diez et al., 2020, Viterbi et al., 2020).

Species inhabiting mountainous regions are particularly vulnerable to the impacts of climate change (Dagnino et al., 2020), potentially elevating their risk of extinction (Schwager and Berg, 2019). Pastorino et al., (2022b) revealed that the occurrence of *Daphnia middendorffiana* (Crustacea, Daphniidae), a species that plays a crucial role in the food chain of high-mountain lakes, could be significantly influenced by the combined impacts of temperature rise and chemical pollution.

Finally, several species, adapted to the cold Alpine climate, are at risk as their habitats shift upward in elevation (Byrne et al., 2014). This can lead to the displacement of native species and the introduction of invasive ones, disrupting the natural balance of high-mountain ecosystems (Byrne et al., 2014).

Recently, Schreder et al. (2023) revealed a noteworthy impact of climate change on the water chemistry of high-altitude lakes in the Alps. In particular, the impact of temperature was notably observed through increases in conductivity, pH, alkalinity, sulfate content, and the overall concentration of ions. These alterations in water chemistry could potentially lead to shifts in the biological dynamics of the lakes, including modifications in the types of species present, thereby initiating a cascade of chemical reactions (Schreder et al., 2023). For example, the examination of subfossil pigments in high-mountain lakes in Bavaria and Tyrol has revealed that the impact of climate change on algal communities is most evident in lakes that are shallow and rich in nutrients (Kuefner et al., 2021). In these types of lakes, the increased thermal energy input results in notable changes in the composition of algae and the accumulation of organic sediments containing pigments. Conversely, deep lakes tend to mitigate these changes due to their larger water volume and ability to retain colder, deeper water layers, which helps to stabilize temperatures in the summer and retain nutrients during stratification (Kuefner et al., 2021).

### 3.2. Retreat of glaciers

The retreat of glaciers serves as an irrefutable indicator of the impact of human activities on the environment (Hock and Huss, 2021). The primary driver of this phenomenon is the emission of greenhouse gases, primarily carbon dioxide, into the atmosphere (Romshoo et al., 2022). The retreat of glaciers is a visible testament to the consequences of our carbon-intensive economies and the pressing need for comprehensive climate action (Romshoo et al., 2022).

The Alps have long been a crucial source of freshwater for the continent (Meisch et al., 2019). Glaciers in this region, acting as frozen reservoirs, play a pivotal role in regulating water supply, especially during the drier summer months (Viani et al., 2020). As temperatures have risen due to the changing climate, glaciers have lost significant mass and volume (Sommer et al., 2020). This phenomenon is especially evident in the accelerated melt rates and glacier shrinkage observed since the mid-20th century. Various studies indicate that glaciers in the Alps have lost approximately 50 % of their ice volume over the last century. Sommer et al. (2020) highlighted a rapid retreat of glaciers throughout the Alps, with an annual loss of ice coverage of 39 $km^2$. These changes in ice thickness vary from a decrease of 0.5 to 0.9 m per year, with the most pronounced thinning occurring in the Swiss Glarus and Lepontine Alps, where specific mass change rates reach as low as −1.03 m of water equivalent per year (Sommer et al., 2020). When considering the entire Alpine region, the estimated mass loss from 2000 to 2014 is approximately 1.3 ± 0.2 gigatons per year (Sommer et al., 2020).

The retreat of glaciers in the Alps is closely intertwined with the hydrological dynamics of high-mountain lakes, and this relationship holds significant implications for the entire Alpine environment (Tiberti et al., 2020). High-mountain lakes, nestled within the towering peaks of the Alps, depend on glacial meltwater as a vital source of freshwater. As these glaciers recede due to global climate change, they directly impact the quantity, timing, and quality of water inflow into these pristine Alpine ecosystems.

Glacial meltwater serves as a critical source of replenishment for high-mountain lakes, especially during the dry summer months. These lakes are highly sensitive to variations in water supply, and the gradual retreat of glaciers has already led to noticeable changes. As glaciers shrink, their contribution to lake levels diminishes, potentially resulting in lower water volumes and more irregular seasonal fluctuations in water levels.

Furthermore, the purity of glacial meltwater is essential to the well-being of high-mountain lakes. This water is typically cold, clear, and low in nutrient concentrations, contributing to the unique and often fragile ecology of these lakes (Tiberti et al., 2020). As glaciers retreat, changes in the chemical composition and temperature of the meltwater can impact the water quality and ecosystem health of high-mountain lakes. For example, Thies et al. (2013) suggested that active rock glaciers release ion-enriched melt waters, export mineral acidity, and induce significant changes in diatom species composition and diversity. Moreover, increased sediment runoff from the melting ice, for example, can cloud the water, reduce light penetration, and negatively affect the aquatic food webs.

In addition to the ecological implications, the retreat of glaciers in the Alps can have socioeconomic consequences for local communities and downstream areas (Beniston and Stoffel, 2014). Many of these communities rely on high-mountain lakes for freshwater supply. A decrease in glacial meltwater input can strain local water resources, potentially leading to conflicts over water allocation and management. Finally, glacier-related hazards, such as glacial lake outburst floods (GLOFs), become more prevalent as glaciers retreat (Romshoo et al., 2022). These floods can pose significant risks to settlements downstream from high-mountain lakes. As glaciers melt and release water into proglacial lakes, the increased water volume can overwhelm natural barriers, potentially resulting in sudden and destructive flooding events.

### 3.3. UV radiation

Solar ultraviolet radiation-UV (290–400 nm) plays a vital role in high-mountain lakes due to its inherent rise in intensity with higher elevations and the exceptional water clarity found in these environments (Sommaruga, 2001). The thin atmosphere and elevated altitudes characteristic of high-mountain environments expose these lakes to higher UV radiation levels compared to lower elevations, making them exceptional indicators of the broader consequences of ozone depletion and climate change (Sommaruga, 2001). This phenomenon is especially noticeable when considering the shorter wavelengths within the UV-B spectrum (290 to 320 nm) (Sommaruga, 2001).

The ozone layer, which acts as Earth's natural sunscreen, is crucial in shielding life from harmful UV radiation (Bernhard et al., 2020). However, this protective layer is not uniform, and depletion of ozone over the past decades has led to increased levels of UV radiation reaching the Earth's surface, with mountain regions being particularly susceptible (Barnes et al., 2019). Ozone-depleting substances, such as chlorofluorocarbons (CFCs), have been controlled by international agreements, resulting in a gradual recovery of the ozone layer (Fang et al., 2019). Still, the legacy of past emissions means that high-mountain lakes continue to face elevated UV radiation levels.

UV radiation in high-mountain lakes poses several significant challenges, foremost among them being the potential harm it inflicts on aquatic life. Biotic populations have evolved several tactics to reduce harm from UV radiation (Niedrist and Füreder, 2023). One of these tactics involves the widespread production or accumulation of various substances that can either directly or indirectly absorb UV radiation (Sommaruga, 2001). While many of the underwater plant and animal species, like those found on the lakebed and in the open water, can cope with intense sunlight, it appears that microorganisms like protists, bacteria, and viruses, which rely on organic matter for sustenance, are notably vulnerable to UV radiation (Carrillo et al., 2002). In particular, phytoplankton is particularly susceptible to UV radiation (Durán et al., 2016). Elevated UV exposure can damage their DNA, inhibit growth, and reduce photosynthetic efficiency (Zhang et al., 2021). Williamson et al. (2020) illustrated the significance of influences of UV radiation and temperature, on the composition of phytoplankton communities in mountain lakes. As phytoplankton populations dwindle, the entire aquatic ecosystem is destabilized, impacting zooplankton, fish, and other organisms higher up the food chain. The consequences reverberate through the entire food web, potentially leading to reduced biodiversity and altered species interactions (Williamson et al., 2020).

The effects of UV radiation extend beyond the aquatic realm, impacting terrestrial ecosystems in the vicinity of high-mountain lakes. Alpine vegetation, including unique and often fragile plant species, can experience UV-induced damage, affecting the composition and functioning of these ecosystems (Sedej et al., 2020). Soil microorganisms, crucial for nutrient cycling and soil health, may also be affected, with potential cascading effects on vegetation (Silva et al., 2022).

Furthermore, UV radiation can intensify the harmful effects of compounds that are susceptible for photoactivation, like polycyclic aromatic hydrocarbons-PAHs (Machate et al., 2023). These changes can negatively affect water quality, making it less suitable for aquatic life, and can influence nutrient availability, further impacting the lakes' ecosystems.

### 3.4. Long-range transport of contaminants and atmospheric deposition

When there are no nearby sources like mountain huts or animals, the water chemistry of high-mountain lakes is primarily influenced by two factors: the deposition of substances from the atmosphere, and the processes happening in the surrounding area that involve the erosion of rocks and soils (Rogora et al., 2020).

The long-range transport of contaminants to high-mountain lakes is a complex and multifaceted environmental issue that poses significant threats to these pristine ecosystems (Battarbee et al., 2005; Catalán, 2015; Machate et al., 2023). High-mountain lakes, situated in remote and seemingly untouched regions, are far from immune to the reach of pollution, as airborne contaminants originating from distant sources can be transported over vast distances and deposited in these remote areas (Catalán, 2015). This phenomenon, often driven by atmospheric and climatic processes, can introduce a range of pollutants into high-mountain lakes, including heavy metals, persistent organic compounds (POPs), nutrients, and microplastics, with far-reaching consequences for water quality, aquatic life, and the broader Alpine environment (Vighi et al., 2007; Catalán, 2015; Pastorino et al., 2023a). This phenomenon is attributed to the lower temperatures at higher altitudes, where precipitation (i.e., rain or snow) serves as an efficient mechanism for transporting water-soluble substances from the atmosphere into mountain lakes and their surrounding environments (Carrera et al., 2002).

One of the key mechanisms of long-range transport is the deposition of airborne pollutants through processes like dry deposition and wet deposition (Daly and Wania, 2005). Dry deposition occurs when airborne particles settle directly onto the lake's surface, while wet deposition involves the removal of contaminants through precipitation (Daly and Wania, 2005). These mechanisms can transport pollutants from both nearby and distant sources, and their deposition can occur on snow and ice surfaces that eventually melt and release contaminants into the lake when the warmer seasons arrive (Carrera et al., 2002).

The chemical composition of water in high-mountain lakes is influenced by various factors such as atmospheric deposition, geological composition, watershed characteristics, biological processes within the lake, and human activities (Mosquera et al., 2022). Crystalline rocks typically lack minerals that readily dissolve, resulting in mountain lakes and headwaters with low levels of salts and limited ability to neutralize acidity, rendering them susceptible to acid deposition. While the ionic concentration remains consistently lower than that of waters in lowland areas, high-mountain lakes situated on metamorphic or carbonate formations can exhibit significant differences in acidity and prevailing ions despite experiencing similar atmospheric deposition influenced by human activities (Catalán et al., 1993). With the onset of the “Great Acceleration” (Steffen et al., 2015), increased emissions of sulfur and nitrogen oxides into the atmosphere have led to the acidification of ecosystems in remote regions, including mountainous areas in Europe (Massabuau et al., 1987). Local and regional studies reveal extensive evidence of acidification in high-mountain lakes. This evidence spans subtle long-term changes, as predicted by critical loads models (i.e., Curtis et al., 2002), to severe biological damage observed in areas with a prolonged history of high acid deposition loads (Rogora et al., 2020). On this path, nitrogen is becoming a more significant contributor to acidification in specific areas like Piedmont Ticino, and its relative significance is expected to grow in other areas as efforts to reduce sulfur deposition across Europe (Curtis et al., 2005).

Heavy metals, such as lead, are among the most concerning pollutants introduced to high-mountain lakes through long-range transport (Tornimbeni and Rogora, 2012). These toxic substances can originate from industrial and urban areas far from the Alpine regions and can accumulate in high-mountain lakes over time (Pastorino et al., 2020). Once deposited, these heavy metals can contaminate the water, leading to potential harm to aquatic life, including phyto-zooplankton, macroinvertebrates and fish, and impacting the overall ecological balance of the lakes (Pastorino et al., 2020). Acidic rock drainage results in a decrease in pH levels and an increase in the presence of specific metals within lakes. Additionally, as temperatures rise, there is a heightened rate of oxidation in sulfide minerals (Moser et al., 2019). However, a study using paleolimnology revealed that deformities in chironomid head capsules due to elevated metal levels were more pronounced during the colder Little Ice Age period compared to the present warmer conditions, as highlighted by Ilyashuk et al. (2018). This research suggests that under higher temperatures, the reduced toxicity of metals to invertebrates offsets the adverse effects of increased sulfide mineral oxidation and acidic rock drainage. These findings underscore the intricate nature of predicting the impacts of warming temperatures on mountain lake ecosystems.

Nutrients, specifically nitrogen and phosphorus compounds, are another class of contaminants introduced to high-mountain lakes through long-range transport (Tiberti et al., 2019). These nutrients can originate from agricultural and industrial sources and are carried by winds and precipitation to the Alpine regions (Battarbee et al., 2005; Tiberti et al., 2019). Excessive nutrient input can lead to eutrophication, causing harmful algal blooms and affecting water clarity and quality. High-mountain lakes are often naturally nutrient-poor, so even small increases in nutrient levels can have significant ecological consequences.

Microplastics, small plastic particles (<5 mm) originating from various sources, have gained attention as emerging contaminants in high-mountain lakes (Pastorino et al., 2022a). These particles can be transported over long distances by winds and atmospheric processes before being deposited in remote Alpine environments (Pastorino et al., 2023a). Their presence in high-mountain lakes is a concern not only due to their persistence in the environment but also because they can adsorb other contaminants, potentially amplifying the impact of multiple pollutants on aquatic ecosystems (Burgos-Aceves et al., 2022; Multisanti et al., 2022; Rahman et al., 2022).

The impacts of long-range transport of contaminants on high-mountain lakes are not confined to their immediate vicinity. These pollutants can affect the entire Alpine ecosystem. Increased contaminant levels can harm aquatic life, disrupt food webs, and alter water quality, posing challenges for both ecological conservation and water supply for downstream community (Pastorino et al., 2023a).

The long-range transport of pollutants poses threats to biodiversity, as it can lead to bioaccumulation in plants and animals, disrupting ecological balances and endangering species (Machate et al., 2023). Moreover, these contaminants can enter freshwater systems, impacting water quality and posing risks to aquatic life (Pastorino et al., 2020).

The unique environmental conditions of high-mountain lakes contribute to the biomagnification of pollutants within the food web. Limited biodiversity and slower metabolic rates in these cold environments result in the accumulation of contaminants in organisms, particularly fish, at higher trophic levels (Schmid et al., 2007; Bartrons Vilamala et al., 2012). This biomagnification process serves as an indicator of the long-range transport and persistence of pollutants (Bartrons Vilamala et al., 2012).

### 3.5. *Impact of alien species on high-mountain lakes*

The impact of alien species (AS) on high-mountain lakes is a growing concern that poses a significant threat to these fragile and pristine ecosystems (Tiberti et al., 2014; Cantonati et al., 2021). Alien species are non-native organisms that, when introduced to a new environment, can outcompete, or disrupt native species, alter ecosystem dynamics, and lead to far-reaching ecological and environmental consequences (Pyšek et al., 2020). High-mountain lakes, often characterized by their isolation, sensitivity to environmental changes, and unique biodiversity, are particularly vulnerable to the introduction of AS (Pastorino and Prearo, 2020). Several factors contribute to the impact of AS on high-mountain lakes:

- introduction pathways: AS can be introduced through various pathways, including human activities such as recreational fishing (Smith et al., 2020). These lakes, though remote, are not immune to the movement of people, equipment, and even unintentional introductions of AS.
- disruption of native ecosystems: AS can outcompete native species for resources such as food, habitat, and breeding sites (Pyšek et al., 2020); this competition can lead to declines in native species, potentially threatening the unique biodiversity of high-mountain lakes. Predatory invasive species like fish, in particular, can have a profound impact on native aquatic fauna, altering the balance of these ecosystems (Tiberti et al., 2014; Pastorino et al., 2019a);
- altered food webs: the introduction of AS can disrupt the food web of high-mountain lakes. For example, alien fish species (particularly trout, and more recently, minnows introduced by anglers for use as live bait) may prey on native zooplankton and macroinvertebrates, leading to population declines (Perilli et al., 2020). The initial recorded instances of introducing fish to the Alps occurred in the middle ages, towards the conclusion of the sixteenth century, likely under the rule of Kaiser Maximilian I (Ventura et al., 2017). These introductions have been widespread and significant, impacting numerous lakes across mountainous regions. These changes can ripple through the ecosystem, potentially impacting other species that depend on the lakes for food (i.e., amphibians);
- changes in water quality: some AS, like certain algae, can alter water quality by depleting oxygen levels and impacting light penetration (Strayer, 2010). These changes can negatively affect the health of native aquatic organisms and lead to shifts in the composition of the ecosystem;
- disease transmission: AS can introduce new diseases or parasites to high-mountain lakes, affecting native species that may not have evolved defenses against these pathogens (Pastorino et al., 2019a). This can lead to disease outbreaks and further contribute to population declines, especially for threatened species like amphibians (Pastorino et al., 2019a).

Efforts to address the impact of AS on high-mountain lakes typically involve prevention, early detection, and management strategies

(Kourantidou et al., 2022). Prevention is crucial and may include regulations to limit the introduction of AS, as well as educational campaigns to raise awareness among visitors. Early detection and rapid response programs help identify AS in their early stages and allow for more effective management and control measures (Marshall Meyers et al., 2020). In this context, high-mountain lakes, being often located in protected areas, can occasionally offer the advantageous local conditions, such as the presence of surveillance personnel, that are necessary for enforcing protective measures like fishing bans and halting restocking, as well as for carrying out restoration projects, such as eradicating invasive fish species (Ventura et al., 2017).

### 3.6. Implications of high-mountain lake water usage for Alpine storage power stations

Hydropower constitutes approximately 10 % of electricity production in the European Union, with Italy accounting for roughly 13.5 % (Gaudard et al., 2014). Hydropower facilities featuring reservoirs play a pivotal role in storing electricity at a relatively low cost (Gaudard et al., 2014). These plants offer flexibility that greatly contributes to the stability of the international grid, managing daily and seasonal load fluctuations, and integrating intermittent energy sources like solar and wind energy (Gaudard et al., 2014). Furthermore, hydropower serves as a significant revenue source for public entities, especially in mountainous regions (Alpine Convention, 2009).

The use of water from high-mountain lakes for storage power stations in the Alps has diverse implications across environmental, social, and economic domains. Environmental impacts include alterations to natural flow patterns, habitat disruption and sedimentation (Haeberli et al., 2016). Socio-economic considerations involve resettlement and cultural heritage preservation. On the positive side, hydropower contributes to renewable energy goals, fosters economic development, and enhances energy security. However, regulatory challenges in balancing development with conservation, as well as the necessity for robust stakeholder engagement, underscore the complexities associated with such projects. Overall, achieving sustainable hydropower development in the Alps requires careful planning, adherence to environmental regulations, and meaningful engagement with stakeholders to mitigate negative impacts and maximize benefits.

### 3.7. Impact of tourism in high-mountain lakes

The impact of tourism on high-mountain lakes in Alpine regions is a complex and multifaceted issue that raises significant environmental and sustainability concerns (Ebner et al., 2022a). The impact of tourism on high-mountain lakes is a multifaceted issue that combines both the allure of these pristine environments and the potential threats they face from human activity (Ebner et al., 2022b). High-mountain lakes, nestled within the majestic landscapes of the world's tallest peaks, draw tourists from around the globe seeking breathtaking vistas, adventure, and tranquility (Schirpke et al., 2021b). While tourism offers economic benefits to local communities and enriches the travel experiences of visitors, it also poses significant challenges to these fragile ecosystems and the surrounding Alpine environment (Schirpke et al., 2021b). The effects of tourism on high-mountain lakes span ecological, social, and environmental dimensions, requiring a balanced approach to ensure the preservation of these exceptional natural wonders (Pastorino and Prearo, 2020).

One of the primary ecological impacts of tourism on high-mountain lakes is the disturbance to the surrounding environment. The construction of trails to accommodate tourists can disrupt fragile ecosystems, destroy habitats, and contribute to soil erosion. The human presence around these lakes, especially during peak tourist seasons (i.e., summer), can lead to trampling of sensitive vegetation, causing soil compaction, and affecting the reproduction and growth of Alpine flora. These areas, characterized by their slow plant growth and sensitive ecosystems, are particularly vulnerable to the physical impacts of visitors. Compacted soil can disrupt the natural hydrological patterns, affecting the flow of water into the lakes and potentially compromising water quality. Wildlife such as nesting birds and small mammals, can be displaced or stressed by increased human activity, potentially leading to population declines.

Water quality is another crucial ecological concern. Tourism often brings an influx of visitors who may not be aware of or adhere to responsible environmental practices. Littering, the improper disposal of waste, and the use of motorized watercraft can lead to pollution and degradation of high-mountain lake waters. Contaminants like nutrients (i.e., N and P), and micro(nano)plastics can find their way into the lakes, impacting water quality and the delicate balance of these ecosystems.

Human activity can also result in the introduction of alien species to high-mountain lakes. Tourists may unknowingly transport non-native species via equipment, clothing, or vehicles, potentially outcompeting or preying upon native aquatic life and altering the ecological dynamics of these fragile ecosystems.

Therefore, tourism has both positive and negative impacts on high-mountain lakes in the Alps. The economic benefits to local communities and the enrichment of visitor experiences must be balanced with the potential ecological, social, and environmental challenges posed by tourism. Sustainable tourism practices and responsible visitor behavior are essential to ensuring the long-term health and preservation of these pristine environments.

The popularity of high-mountain lakes has also led to an increase in recreational activities, including fishing. While these activities can foster a deeper appreciation for these environments, they may also result in disturbances to wildlife, including nesting birds, mammals, and aquatic species.

## 4. Future research directions on high-mountain lakes in the Alps

Despite the ecological and environmental significance of high-mountain lakes, there are still many knowledge gaps on these key ecosystems. Fig. 2a illustrates that 192 documents are available from 1988 to 2024 on high-mountain lakes located in the Alps (Scopus database: https://www.scopus.com/search/form.uri#basic; search keywords: "high-mountain" OR "high-altitude" AND "lakes" AND "Alps" AND "Europe" OR "European" OR "Alpine"). However, an in deep analysis of documents (only considering those related to high-mountain lakes *sensu stricto*) allowed to select 160 documents (original research article and review) (Table S1; Supplementary Material). Fig. 2b illustrates the main 10 journals (*Journal of Paleolimnology*, *Quaternary Science Reviews*, *Hydrobiologia*, *Journal of Limnology*, *Science of the Total Environment*, *Aquatic Sciences*, *Environmental Science and Technology, Archiv Fur Hydrobiologie*, *Arctic Antarctic and Alpine Research* and *Freshwater Biology*) in which the documents found on Scopus were published, whereas Fig. 2c illustrates the top 11 Authors (Psenner, R., Marchetto, A., Boggero, A., Sommaruga, R., Arnaud, F., Pastorino, P., Tiberti, R., Grimalt, J.O., Mosello, R., Catalán, J. and Rogora, M.) who are currently making contributions to the provision of information on the biology, ecology, ecotoxicology, geomorphology, and environmental chemistry of high-mountain lakes. A critical and objective analysis of these documents (Table S1; Supplementary Material) reveals that the majority of them are solely focused on one or a few environmental components (biotic or abiotic) without employing a multidisciplinary approach. Indeed, research on high-mountain lakes requires interdisciplinary collaboration, combining expertise in ecology, limnology, glaciology, climatology, and more. This holistic approach is necessary to fully understand the impact of global change in these ecosystems (Pastorino et al., 2023b). Through continued research, conservation efforts, and global collaboration, we can ensure that these pristine altitude ecosystems endure as indicators, not only of change but also of our collective responsibility to protect the planet for future generations.

Monitoring and research programs in high-mountain lakes are

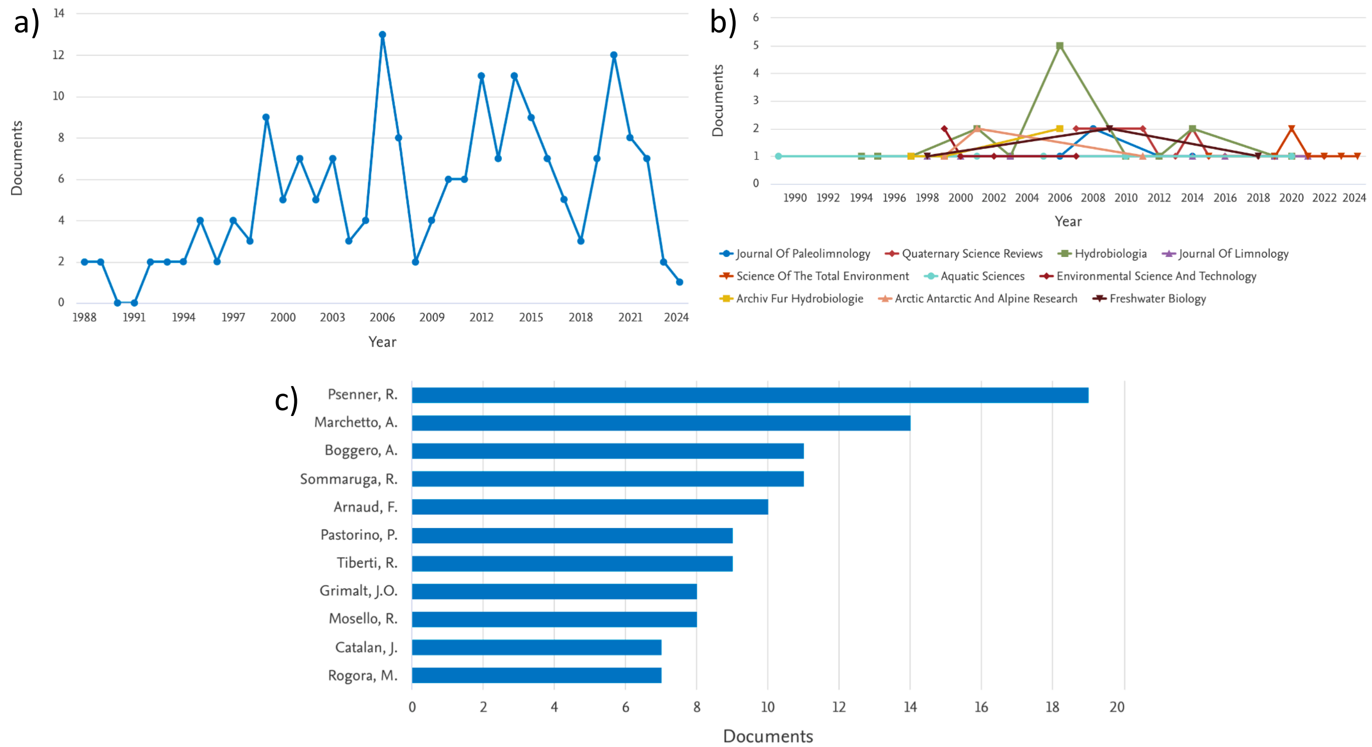


**Fig. 2.** Results of literature search on high-mountain lakes located in the Alps (Scopus database; https://www.scopus.com/search/form.uri#basic): a) number of published documents per year (1988–2024); b) number of published documents per year (1988–2024) in the main 10 journals (each color represents a journal); c) number of documents published in the period 1988–2024 by the 11 main Authors.

essential for understanding the ecological health of these pristine environments, assessing the impact of environmental changes, and formulating effective conservation strategies (Pastorino and Prearo, 2020). These strategies encompass a wide range of scientific and observational activities aimed at gathering data on water quality, hydrology, biodiversity, and the factors that affect these high-altitude ecosystems. Some of the key components of monitoring and research initiatives in high-mountain lakes could include:

- water quality monitoring: continuous monitoring of water quality parameters such as temperature, pH, conductivity, dissolved oxygen, nutrient and contaminants levels is crucial for understanding the state of high-mountain lakes. Changes in water quality can provide early indications of pollution or ecological disturbances;
- hydrological studies: monitoring water flow, water level fluctuations, and the timing of snowmelt and glacial runoff is essential for assessing the hydrological dynamics of high-mountain lakes. This information helps understand the sources of water, its seasonal variability, and the impact of climate change;
- biodiversity surveys: initiatives often include biodiversity surveys to document the species present in and around high-mountain lakes. This may involve studying aquatic organisms like fish, macroinvertebrates, and phyto-zooplankton, as well as terrestrial flora and fauna in the surrounding environment;
- climate monitoring: continuous climate monitoring, including temperature trends, precipitation patterns, and glacial retreat rates, helps researchers understand the broader environmental context in which these lakes exist;
- glacial monitoring: many high-mountain lakes receive water input from glaciers. Monitoring the size, movement, and health of glaciers is essential for assessing their impact on lake water supply, as well as the potential release of glacial meltwater and sediments;
- long-term research: long-term studies provide invaluable data on trends and changes in high-mountain lakes over time. This longitudinal research helps identify patterns, such as the effects of climate change, and assesses the response of these ecosystems to various stressors;
- remote sensing and technology: advances in remote sensing technology, including satellite imagery and unmanned aerial vehicles (UAVs), have enabled scientists to monitor high-mountain lakes from a distance, collecting data on water levels, ice cover, and environmental changes;
- ecosystem modeling: mathematical models and simulations can be used to predict the response of high-mountain lake ecosystems to various stressors and to assess potential future scenarios;
- collaboration and international cooperation: high-mountain ecosystems often span national borders, necessitating international collaboration for comprehensive monitoring and research.
- citizen science and collaborative research: engaging local communities and citizen scientists in monitoring efforts enhances data collection and fosters a sense of stewardship.

Such monitoring and research strategies not only contribute to a better understanding of high-mountain lakes but also aid in the development of conservation and management strategies. By comprehensively studying these fragile ecosystems, scientists and policymakers can make informed decisions to protect these invaluable natural resources in the face of emerging threats and environmental changes, ensuring the long-term sustainability of high-mountain lakes and the surrounding Alpine environment.

## 5. Conclusion

High-mountain lakes in the Alps play a vital ecological and environmental role, yet significant knowledge gaps persist regarding these critical ecosystems. As state above, current literature indicates a predominant focus on individual environmental aspects, lacking a holistic, inter/multidisciplinary approach. Thus, continued research, conservation endeavours, and global cooperation are pivotal in ensuring the endurance of these altitude ecosystems as indicators of environmental change and our collective responsibility towards planetary protection.

Monitoring and research programmes are indispensable for assessing the ecological health of high-mountain lakes, understanding environmental changes, and formulating effective conservation strategies. These initiatives encompass various scientific activities, including continuous water quality monitoring, hydrological studies, biodiversity surveys, climate monitoring, glacial monitoring, long-term research, remote sensing technology utilization, ecosystem modelling, and international collaboration. Engaging local communities and citizen scientists further enriches data collection and fosters stewardship. These strategies not only advance our understanding of high-mountain lakes but also inform conservation and management strategies, ensuring the long-term sustainability of these fragile ecosystems and the surrounding Alpine environment.

## CRediT authorship contribution statement

**Paolo Pastorino:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Data curation, Conceptualization. **Antonia Concetta Elia:** Writing – review & editing, Writing – original draft, Conceptualization. **Elisabetta Pizzul:** Writing – review & editing, Conceptualization. **Marco Bertoli:** Writing – review & editing, Conceptualization. **Monia Renzi:** Writing – review & editing. **Marino Prearo:** Writing – review & editing, Supervision, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

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