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Climate change: impact on lake ecosystems

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ABSTRACT

Freshwater lakes are among the most valuable and sensitive components of the Earth's ecosystems, providing essential services such as drinking water, food production, climate regulation, biodiversity support, and recreational benefits. Despite occupying a relatively small proportion of the global land surface, lakes play a disproportionately large role in biogeochemical cycling and regional climate processes. However, these ecosystems are increasingly threatened by climate change, which acts both as a direct stressor and as a catalyst that amplifies existing anthropogenic pressures such as nutrient enrichment, land-use change, and water extraction. Climate change influences lake ecosystems through interconnected physical, chemical, and biological pathways. Rising air temperatures alter thermal regimes, strengthening and prolonging stratification. Changes in precipitation patterns and increased frequency of extreme events such as droughts, heatwaves and intense rainfall modify the hydrological inputs, water levels, and residence times. Enhanced evaporation further disrupts lake water balance, particularly in shallow and closed systems. These physical changes cascade into alterations in water quality, nutrient cycling, and dissolved oxygen dynamics. Beyond ecological impacts, climate-driven lake degradation has significant socioeconomic consequences. Declining water quality, reduced fish yields, and diminished recreational value threaten human health, food security and livelihoods. Particularly in vulnerable regions. This review synthesises current knowledge on climate-induced changes in lake ecosystems, highlighting the key mechanisms, feedbacks and research gaps and underscores the urgent need for integrated management and adaptive strategies to safeguard lake ecosystems in a warming world.

Keywords: *Climate change, Thermal stratification, Hydrological variability, Eutrophication, Harmful algal blooms, Biodiversity dynamics.*

1. Introduction

Fresh water lakes are one of the most sensitive and valuable components of our ecosystems. These are providing critical services such as drinking water, food production through agriculture, fisheries. These lakes also regulate the climate, supports the biodiversity, cultural and recreational benefits.

Despite covering a small fraction of the global land cover, lakes play a dis proportionate role in biogeochemical cycling, regional climate moderation and socio-economic wellbeing. In recent decades, lake eco systems worldwide have been increasingly threatened by climate variations, which acts both as a direct stressor and as a catalyst that amplifies existing anthropogenic stress such as nutrient enrichment, land-use change and water extraction for many purposes.

Climate change effects lake ecosystems through many interlinked ways. Increasing atmospheric air temperatures alter lake thermal regimes, intensify and extend stratification, decrease ice-cover time in cold regions. Climate change also increase the frequency of extreme events such as heat waves, droughts and heavy rainfalls. Changes in precipitations patterns modify hydrological inputs, water levels and residence time of water. While enhanced evaporations and Evo-transpirations affects lake water balance and salinity, in particular shallow and closed basin systems. All together, these physical changes drive cascading effects on water quality, nutrient cycling, dissolved oxygen dynamics and biological communities.

A growing body of evidence demonstrates that the change in climate speeding up the fundamental shifts in lake functionality. Warming water reduces oxygen solubility and, when combined with stronger stratification promote hypoxia and anoxia in deeper layers. Altered mixing and hydrology influence the nutrient availability. Often, enhancing internal nutrient loading will be the susceptibility of lakes to eutrophication and harmful algal blooms like freshwater cyanobacteria (*Microcystis*) and marine red tides (*Karenia brevis*). At the same time, climate driven changes in thermal habitats and water quality are re-shaping the biodiversity patterns, re-organising food webs and affecting fisheries production and the ecosystem's stability.

Beyond ecological consequences, climate -affected lake degradation has considerable socio-economic implications. Reducing water quality threatens drinking water safety, increasing algal blooms impairs recreation and tourism and changing fish production undermines the food security and livelihoods for lake dependent communities. These impacts are un evenly distributed and disproportionally affecting areas with high climate sensitivity and limited adaptive capacity. Thereby linking the lake ecosystem change to broader issues of environmental justice and sustainable development.

Given the rapid pace of climate change and the important role of lakes in coupled human-natural systems, there in an urgent requirement to synthesize present knowledge on how climate change affects lake eco systems. This review aims to provide a comprehensive assessment of climate-driven changes in lake physical processes, hydrology, water quality, biogeochemical cycles, biodiversity and ecosystem services. By integrating recent empirical evidence, modelling studies and emerging monitoring approaches, the review highlights key mechanisms, regional patterns, feedbacks and knowledge gaps. Ultimately, it seeks to inform climate response lake conservation, policy strategies and management to safeguard lake ecosystems in a warming world.

2. Thermal structure and mixing

Lake thermal structure and mixing dynamics are fundamental regulators of physical, chemical and biological processes within the lake ecosystem. The rising air temperatures, altered wind regimes, changes in precipitation patterns, and shifting ice cover dynamics have emerged as a dominant driver modifying lake stratification, mixing regimes and heat storage. These changes have profound implications for oxygen distribution, nutrient cycling, and overall ecosystem functioning. The thermal behaviour of lakes is governed by the balance between stratification and mixing processes which together determine energy distribution within the waster column and regulate vertical transport of oxygen and nutrients. Thermal stratification typically occurs when warm and lighter water overlies colder and denser water during warmer months creating layers like epilimnion, metalimnion, hypolimnion are separated by a thermocline. Seasonal mixing events disrupt this structure enabling vertical exchange and ecosystem renewal. As a result of changes, the timing and intensity of these processes are reshaping lake ecology, water quality and associated ecosystem services.

Air temperature remains the primary driver of lake surface warming and stratification dynamics. Studies have indicated that the lake surface temperatures increase at ~ 0.7-0.8 C for every 1C rise in temperature. This leads to accelerated warming od surface layers relative to deeper waters. Thereby enhancing stratification stability, delays sin seasonal, and extended stratified periods. More recent studies have suggested that lake surface temperatures are rising at rates of 0.34 C per decade often exceeding atmospheric warming trends, implying the sensitivity of inland waters [1].

Wind stress plays a critical but regionally variable role in modulating stratification. Wind-driven shear can erode thermal gradients and promote vertical mixing, particularly in shallow or large lakes with high fetch. However, declining wind speeds observed in several regions have reduced mixing intensity, reinforcing stratification and limiting oxygen transport to deeper layers [2]. The interaction between buoyancy (driven by temperature differences) and wind stress ultimately determines mixing depth, and this balance varies with lake morphology, exposure, and regional climatic trends.

In cold and temperate regions, reductions in ice-cover duration represent one of the most pronounced climate-driven shifts in lake thermal regimes. Earlier ice-off and delayed freeze-up extend the open-water season, advancing spring stratification and postponing autumn turnover, thereby lengthening the stratified period. These changes are already altering traditional mixing classifications, with some dimictic lakes transitioning toward meromictic or even oligomictic behavior. Such shifts indicate a breakdown of historical thermal regimes and the emergence of novel lake states under continued warming *(Environ.* 2021). Precipitation patterns influence thermal structure indirectly through hydrological inputs and density gradients. Increased runoff may introduce cooler inflows that temporarily weaken stratification, while extreme rainfall events can induce short-term mixing, resuspension, and disruption of stable thermal layers. Conversely, prolonged dry periods reduce inflow and enhance thermal stability by minimising external disturbances. Although historically understudied relative to temperature and wind effects, hydrological variability is now recognised as an important control on lake thermal dynamics, particularly in climate-sensitive regions [3].

In addition, climate warming also intensifies vertical density gradients, leading to stronger and more persistent stratification that reduces the proportion of the water column interacting with the atmosphere. As a result, oxygen replenishment in hypolimnetic waters is increasingly limited, particularly in deep lakes. Many temperate systems now exhibit enhanced thermal resistance to mixing, with surface layers warming faster than deeper waters, further inhibiting vertical exchange [4]. Climate warming also intensifies vertical density gradients, leading to stronger and more persistent stratification that reduces the proportion of the water column interacting with the atmosphere. As a result, oxygen replenishment in hypolimnetic waters is increasingly limited, particularly in deep lakes. Many temperate systems now exhibit enhanced thermal resistance to mixing, with surface layers warming faster than deeper waters, further inhibiting vertical exchange [4]. Prolonged stratification isolates hypolimnetic waters, reducing oxygen replenishment and increasing the risk of hypoxia or anoxia. Oxygen depletion affects nutrient cycling, potentially releasing phosphorus from sediments and fuelling algal blooms once mixing resumes. Warm surface temperatures also reduce oxygen solubility, compounding low oxygen stress [5].

The ecological consequences of altered thermal structure are significant and far-reaching. Prolonged stratification isolates hypolimnetic waters, reducing oxygen availability and increasing the risk of hypoxia or anoxia, particularly during extended summer periods. Oxygen depletion promotes the release of phosphorus and other nutrients from sediments, enhancing internal loading and increasing the likelihood of eutrophication and harmful algal blooms upon mixing. Additionally, warmer surface waters reduce oxygen solubility, compounding stress on aquatic organisms. Changes in stratification timing and intensity also directly influence phytoplankton dynamics and broader food web interactions. Earlier onset of stratification alters light and nutrient availability, often favouring buoyant and bloom-forming cyanobacteria, while reduced mixing limits nutrient redistribution to surface waters later in the season. These shifts can restructure plankton communities, disrupt trophic interactions, and ultimately affect fish habitat and productivity [4].

Advances in process-based and climate-driven lake models provide further insight into future trajectories. Simulations consistently project continued increases in surface temperature, stratification strength, and duration of stratified periods across diverse lake systems. Despite significant progress, several key knowledge gaps remain. High-latitude and polar lakes are still underrepresented in long-term datasets, limiting understanding of extreme climate responses [6].

Interactions between thermal dynamics and watershed processes, including runoff, sediment transport, and nutrient fluxes, remain insufficiently integrated in current studies. Furthermore, the impacts of episodic extreme events-such as heatwaves, storms, and rapid hydrological shifts-on stratification and mixing dynamics require more detailed investigation.

3. Changes in lake hydrology and water balance

Lakes are dynamic hydrological systems regulated by the balance between inflows, outflows, water levels and residence times. Changes in precipitation patterns, snow melting, and increased evaporation collectively alter the balance between water inputs and losses, thereby reshaping lake hydrology. Observational studies indicate that evaporation has increased by 5-10% in many temperate and subtropical lakes, while hydrological extremes such as prolonged drought or heavy precipitation events can cause water level fluctuations of up to 1-2 m. These hydrological shifts do not affect all lakes uniformly but instead depend strongly on lake morphology and hydrological setting. Shallow lakes are particularly sensitive ; low water levels concentrate nutrients, expose littoral zones and alter habitat availability for aquatic organisms. In contrast, deep lakes may retain volume but experience reduced flushing, which enhances internal nutrient recycling and increases susceptibility to eutrophication and algal blooms. It is further intensified by human water consumption for irrigation, industrial and municipal use. At regional scale, the relative balance between precipitation and evaporation determines the direction and magnitude of changes in level of lake. In semi-arid and Mediterranean climates, precipitation with higher evaporation rates leads to lower mean lake levels and sometimes the exposure of shallow littoral zones. Conversely, regions experiencing increased storm frequency or intensity may witness episodic rises in water level, altering shoreline habitats and sediment resuspension [4]. Such fluctuations can destabilise ecosystems, impact fish spawning grounds and change the spatial distribution of aquatic vegetation. Besides this, changes in the catchment hydrology also play a major role. Warmer winter reduces snow accumulation in temperate and boreal watersheds, resulting in earlier snowmelt and shifts in the timing of peak inflows. Earlier and sometimes more rapid spring runoff can elevate lakes' water levels temporarily, followed by extended summer low-water conditions. This seasonal redistribution of inflows alters residence time and stratification patterns. Lakes with short residence times may experience drastic changes in nutrient loading and water chemistry because inflows dominate the water balance. Whereas lakes with longer residence times may be buffered against short-term precipitation variability but remain susceptible to evaporation effects. Groundwater and lake interactions provide an additional complexity in regulating water balance responses. Lakes strongly linked to ground water systems may maintain relatively stable water levels during dry periods, whereas hydrologically isolated lakes that depend on runoff are susceptible to fluctuations. Declining recharge under warmer and dry conditions can reduce baseflow contributions, pushing towards evaporation-dominated regimes [7]. The combined influence of climate variability and human water use becomes particularly evident in large lake. For instance, Lake Titicaca, one of the worlds' largest high-altitude lakes show precipitation and evaporation are the dominant controls on its water balance [8]. Similarly, lake Balkhash in central Asia demonstrates the variability as a result of human water use, where climate-driven increase in water availability have been nearly offset by ling-term extraction, resulting in fragile hydrological balance [9]. Studies from Iranian lake further indicate that reduced inflows combined with irrigation pressures can accelerate shrinkage [10]. Isotope-based investigations further show that temperature and precipitation regulate evaporation and inflow. Superimposed on these gradual changes, increasing hydrological extremes are intensifying lake water balance. Rising temperatures enhance evaporation and evapotranspiration while declining snowpack and altered rainfall patterns reduce the predictability of runoff in many basins [10]. Reduced infiltration further limits groundwater recharge [11]. Droughts led to sustained reductions in inflow and water levels, whereas floods may temporarily increase lake volume but often introduce high nutrient and sediments loads. New hydrological modelling techniques, such as process-based models like SWAT, Budyko-type frameworks, and machine learning-integrated approaches, are improving the quantification methods [9]. These tools enable the separation of climate-driven effects from human influences to accurately predict future water conditions.

4. Lake water quality parameters

Lake water is closely governed by variations in thermal structure, mixing dynamics and hydrological processes. This makes it highly responsive to ongoing environmental shifts. Variations in temperature, stratification intensity and water residence time collectively influence oxygen dynamics, nutrient availability, primary productivity among others. As a result, even subtle shifts in physical conditions can trigger disproportionate changes in chemical and biological parameters.

Among the most sensitive indicators, dissolved oxygen reflects the combined effects of stratification and biological activity. Prolonged thermal stratification increasingly restricts vertical mixing, isolating hypolimnetic waters from atmospheric exchange. This leads to a gradual decline in oxygen concentrations in deeper layers with reported decreases of 0.5-1 mg/L per decade in many stratified lakes [12]. Reduced oxygen solubility at higher temperatures, coupled with enhanced microbial respiration and organic matter decomposition, further accelerates oxygen depletion frequently resulting in hypoxic or anoxic conditions [13]. The oxygen dynamics are closely linked to nutrient cycling particularly the mobilisation of phosphorus from bottom sediments. Under low oxygen conditions, redox sensitive release sediment bound phosphorus into the water column increasing nutrient concentrations in the hypolimnion. Subsequent mixing events redistribute these nutrients into surface water stimulating phytoplankton growth and reinforcing eutrophic conditions [14].

Changes in temperature and nutrient availability also strong influence phytoplankton composition and productivity. Warmer more stable surface waters favour for proliferation of cyanobacteria which are well adapted to stratified conditions due to their buoyancy regulation, efficient nutrient uptake and tolerance to elevated temperatures. Over recent decades algal biomass has increase by approximately 20-30% in many eutrophic lakes with cyanobacterial blooms becoming more frequent and persistent.

These blooms reduce water transparency, later light penetration and produce toxins such as microcystins posing risks to aquatic life, drinking water quality and public health.

Hydrological variability further modulates water quality responses. Increased residence time during low flow periods allows nutrient accumulation and prolonged biological activity. Whereas high inflow events can introduce external nutrient loads, suspended sediments and dissolved organic matter. Intense rainfall and storm events may trigger episodic mixing and sediment resuspension, leading to short-term increases in turbidity and nutrient availability. Conversely, extend dry periods can concentrate solutes and enhance evaporation effects further altering chemical conditions.

Other parameters such as pH, conductivity and dissolved organic carbon are also affected. Elevated temperatures and enhanced primary production can lead to increased pH on surface waters. Shifts in catchment inputs influence organic carbon concentrations and light attenuation. The changes although often gradual can significantly affect species composition, microbial processes and over ecosystem. Most long term observational records are concentrated in temperate regions and lakes in tropical, sub-tropical and high altitude environments remain unexplored.

5. Nutrient enrichment, and eutrophication dynamics

Eutrophication, defined as the excessive enrichment of water bodies with nutrients such as nitrogen and phosphorus remain one of the leading causes of freshwater degradation worldwide. It leads to increased primary production, algal blooms, oxygen depletion, and deterioration of water quality. Conventionally, external nutrient loading from agricultural runoff and wastewater has long been recognised as the dominant factor. However, recent studies increasingly recognise eutrophication as a coupled process where warming, altered hydrology interact to modify algal bloom dynamics [15]. One of the primary mechanisms linking environmental change to eutrophication is the enhancement of internal nutrient loading. Elevated temperatures accelerate microbial metabolism and organic matter decomposition, leading to increased release of inorganic nitrogen and phosphorus from lake sediments. Mesocosm and experimental studies show that this temperature-driven nutrient release is particularly pronounced in shallow lakes, where sediment-water interactions are strong and rapidly influence overlying water chemistry [16]. At the same time, stronger and more persistent thermal stratification reduces vertical mixing, promoting hypoxic or anoxic conditions in bottom waters. Under such conditions, phosphorus bound to sediments is released into the overlying water, increasing nutrient availability and reinforcing eutrophic conditions [17]. This internally regenerated nutrient pool can sustain algal growth even when external inputs are relatively stable. Hydrological variability further influences nutrient delivery and retention within lakes. Increased frequency of intense rainfall and flooding events enhances nutrient transport from catchments, mobilizing fertilizers, organic matter, and sediments into lake systems [18]. Such episodic inputs often trigger short-term but intense phytoplankton responses, particularly when they coincide with favourable thermal conditions. In contrast, reduced inflows and extended residence times during dry periods promote nutrient accumulation and prolonged biological activity. At broader spatial scales, observational and satellite-based studies indicate a global increase in algal bloom frequency over recent decades, particularly in subtropical and warm regions. These large-scale patterns demonstrate that rising temperatures can amplify eutrophication outcomes even in systems where nutrient inputs are relatively low [19].

Eutrophication also drives substantial changes in biological communities and ecosystem structure. Warmer, nutrient-rich conditions favour cyanobacteria and other eutrophic-tolerant taxa, which possess adaptive traits such as buoyancy regulation and tolerance to high temperatures. Experimental evidence further suggests that combined warming and nutrient enrichment increase variability in plankton communities, shift bacterioplankton and phytoplankton composition, and promote species associated with eutrophic conditions [20]. Over longer timescales, these shifts can destabilise ecological networks, reduce resilience, and simplify food web structure. Such changes are increasingly linked to reduced ecosystem stability and altered energy transfer within aquatic food webs [18]. The increasing occurrence of harmful algal blooms also represents a major ecological and socio-economic concern. Cyanobacterial blooms can produce toxins that threaten aquatic organisms, drinking water safety, and recreational use. In addition, warming enhances the frequency, duration, and intensity of these algal blooms [14]. The decomposition of excess organic matter contributes to oxygen depletion, further stressing aquatic life and reinforcing nutrient release through positive feedback mechanisms [4]. Long-term observations from managed lake systems reveal that recovery from eutrophication is often complex and, in some cases, reversible. Reductions in external nutrient inputs have not always led to sustained improvements in water quality. As the internal nutrient loading and persistent anoxia can drive re-eutrophication [21].

Besides this, eutrophication responses also vary across regions with tropical, subtropical, and arid lakes often higher sensitivity due to stronger warming trends and intensified nutrient pressures. Global projections suggest that eutrophication risk, particularly phosphorus-driven enrichment is likely to increase in future [14].

6. Biodiversity responses and food web recognition

Rising water temperatures directly influence metabolic rates, species' physiological thresholds, and life-history traits. Species adapted to cold, oxygen-rich habitats are particularly vulnerable, often experiencing declines or local extinctions as habitats warm and stratification intensifies. This thermal shift enables more thermally tolerant species, including invasive taxa, to expand, often at the expense of native biodiversity. Such shifts are not merely compositional but represent directional ecological changes that can permanently alter community structure and function [22].

Warming also interacts with nutrient inputs to favour harmful algal blooms, which alter primary producer communities, reduce water quality, and trigger hypoxia. These changes disrupt trophic linkages by reducing food quality for zooplankton and fish, contributing to simplified food webs dominated by tolerant or opportunistic species [23]. As a result, energy transfer efficiency from primary producers to higher trophic levels declines, weakening the overall functioning of the ecosystem [14]. Studies document that warming waters are associated with significant changes in community composition, including shifts in fish phenology and migration timing in large lake systems, indicating consistent directional change rather than cyclical variability [24].

At broader scales, nearly a quarter of freshwater animal species, including fish, crustaceans, and aquatic insects, are now at high risk of extinction, a pattern amplified by the combined effects of warming, habitat loss, and pollution [24]. Certain taxa respond rapidly to environmental change and can serve as early indicators. For example, changes in chironomid (non-biting midge) communities reflect long-term temperature trends in boreal and subarctic lakes, with species turnover closely linked to thermal preferences. Similarly, shifts in macrophyte communities demonstrate how local environmental conditions interact with broader climatic drivers to influence biodiversity and ecosystem stability in complex ways (arXiv). Recent studies show that warming and nutrient enrichment interact to simplify food webs in lakes and streams. These stressors reduce food chain length and network connectome, favouring shorter and less complex trophic structures with fewer links between primary producers and top predators [13]. This reduces redundancy within ecological networks, making ecosystems more vulnerable to disturbances and less capable of maintaining functional stability [16].

In plankton communities of multiple Swiss lakes, warming has been shown to reduce network interactions, shifting trophic control from consumers to resource-driven systems and enabling opportunistic taxa such as small grazers and cyanobacteria to dominate. Long-term warming can directly alter predator–prey dynamics. For example, in Lake Maggiore (Italy), increased temperatures supported greater abundance of intermediate predators such as the spiny water flea, which suppressed keystone grazers like Daphnia, thereby weakening top-down control and promoting algal growth [19]. These alterations highlight how subtle shifts at one trophic level can cascade through the entire food web. Warming also affects energy transfer across trophic levels. Warmer lakes tend to support greater phytoplankton biomass relative to fish biomass, indicating a decoupling of energy flow from primary producers to higher trophic levels and potentially reducing fish production [20]. This imbalance reflects reduced trophic efficiency and a shift toward bottom-heavy ecosystems dominated by primary producers.

Simplified food webs with weakened trophic linkages often exhibit reduced resilience to disturbances. Shorter food chains and dominance by tolerant species can impair nutrient cycling, decrease stability, and increase the likelihood of regime shifts, including persistent algal blooms or hypoxic conditions. Such systems are more prone to abrupt and potentially irreversible ecological transitions [15]. Changing environmental conditions may also lead to the emergence of novel food webs, characterised by new species combinations, particularly where invasive species gain competitive advantages or native species decline.

7. Climate impact on fishery potential and aesthetic quality of lakes

Large-scale analyses across more than 12,000 lakes in the United States show that cold-water fish species are losing suitable thermal habitat faster than warm-water species are gaining it, reflecting asymmetric warming and increasing homogenization of thermal regimes [20]. At regional scales, modelling studies further demonstrate declining habitat suitability under future scenarios. For example, projections for Loktak Lake (India) indicate a substantial reduction in suitable habitats for key fish species due to increasing temperatures and altered hydrological regimes. Such changes not only redistribute species but also reduce overall fishery productivity and stability. Thermal stratification further constrains fish production by limiting vertical mixing and reducing nutrient transport to surface waters.

Water quality degradation further amplifies these impacts. Reduced oxygen availability under prolonged stratification can directly threaten fisheries and aquaculture [23]. Toxic blooms not only affect fish health but also reduce the economic value of fisheries through mortality events and contamination risks. In addition, environmental change alters the aesthetic quality of lakes.

Heatwaves and droughts have been linked to exceptionally high water temperatures and mass fish mortality events, such as those reported in Amazonian lakes. These abrupt disturbances not only disrupt ecological processes but also severely degrade public perception and usability of lake environments. Oxygen depletion and organic matter accumulation can further result in turbid, foul-smelling conditions. The combined impacts on fisheries and aesthetics have significant socio-economic implications. Declining suitability for cold-water species threatens fishery yields and food security. The shifts in species composition require adaptation in fishing practices and livelihoods.

8. Socio economic impacts of climate driven lake degradation

Changes in temperature, precipitation, and evaporation are modifying lake water levels, seasonality, and availability. For instance, long-term observations from Poyang Lake (China) demonstrate how warming and shifting rainfall patterns alter hydrological regimes, affecting irrigation reliability, drinking water access, and agricultural productivity. Declining lake volumes observed globally are intensifying competition among domestic, agricultural, and industrial water users, with direct implications for food production and regional economic stability. Fisheries, one of the most climate-sensitive lake services, are already showing measurable declines. Variations in temperature and precipitation have been linked to reduced fish catch across multiple regions, particularly in Sub-Saharan Africa, Southeast Asia, and Latin America (USGS). A case study from Lake Kariba (Zambia–Zimbabwe) highlights how drought-driven water level declines disrupt fish habitats, reduce catches, and directly affect household income among fishing communities [25].

In colder regions, seasonal ice cover supports winter-based economies such as ice fishing and tourism. Projected reductions in ice duration are expected to shorten these seasonal activities, with economic losses estimated in the billions annually. Similarly, extreme events such as floods and storms are increasing in frequency and intensity, causing damage to infrastructure, settlements, and local economies. Evidence from the Lake Victoria basin (Kenya) shows how flooding events have led to widespread socio-economic disruption, disproportionately affecting lakeside communities [26].

Environmental degradation is already reshaping livelihoods. Household-level studies around Lake Dambal indicate that water scarcity, invasive species, and declining land productivity are increasing economic risk and forcing shifts in agricultural practices [33]. In Loktak Lake (India), ecological deterioration has driven livelihood diversification, with communities moving away from traditional fishing and farming systems toward alternative income sources [27].

While adaptive, these transitions often come with social and economic costs, including loss of cultural identity and increased vulnerability.

Extreme thermal events can trigger ecosystem-level collapse with cascading human impacts. Reports from Amazonian lakes describe water temperatures exceeding 40 °C, resulting in mass mortality of fish and aquatic fauna, which directly threatens local food systems and nutrition. Declines in freshwater fisheries, a major protein source for millions, can force households to rely on less nutritious alternatives or migrate in search of income. Beyond local impacts, lake degradation affects regional economies through reduced tourism, declining water quality, and diminished ecosystem services. Aesthetic degradation, harmful algal blooms, and water scarcity can reduce recreational use and economic returns. These impacts are often unevenly distributed, with low-income and marginalised communities facing disproportionately higher risks due to limited adaptive capacity.

9. Climate adaption and mitigation strategies

Adaptation strategies aim to enhance resilience and reduce vulnerability under changing environmental conditions. Nature-based solutions (NbS), such as wetland restoration, riparian buffer establishment, and littoral vegetation recovery, play a critical role in stabilising shorelines, filtering nutrients, and maintaining habitat complexity. They not only improve ecological integrity but also provide co-benefits such as biodiversity conservation and recreational enhancement.

Ecosystem-based adaptation (EbA) extends this approach by integrating ecosystem processes into broader climate strategies. For example, maintaining healthy catchments can reduce nutrient inflows and buffer against hydrological extremes, thereby mitigating both water quality degradation and climate impacts. Integrated Water Resources Management (IWRM) is another key framework, enabling coordination across sectors and scales. By linking land-use planning, surface and groundwater management, and climate adaptation strategies, IWRM provides a holistic approach to managing lake catchments [23]. Adaptive governance frameworks that incorporate real-time monitoring, early warning systems for hypoxia or algal blooms, and flexible policy responses are essential under uncertain future conditions.

Advances in modelling are improving predictive capacity. Process-based and ensemble models, such as those developed under global initiatives like ISIMIP, allow simulation of lake responses under different climate scenarios, supporting decision-making and evaluation of management interventions [28]. Mitigation strategies focus on reducing drivers that amplify climate impacts.

Controlling nutrient inputs, particularly nitrogen and phosphorus, is critical to limiting eutrophication and associated greenhouse gas emissions such as methane (OUCI). Lakes and associated wetlands also act as carbon sinks, storing organic carbon in sediments. Protecting and restoring these systems enhances carbon sequestration while improving water quality and biodiversity [3].

Technological interventions, including advanced wastewater treatment and engineered nutrient removal systems, can complement ecological approaches. In some cases, targeted engineering solutions such as hypolimnetic oxygenation or selective water withdrawal may help counteract localised impacts [25]. Translating scientific knowledge into policy, integrating socio-economic considerations, and ensuring long-term monitoring are ongoing challenges.

10. Emerging technologies and future research directions

Satellite-based remote sensing platforms, including systems such as Sentinel and MODIS, provide large-scale observations of key water quality parameters such as chlorophyll-a, turbidity, and surface temperature. These tools enable continuous monitoring of eutrophication and algal blooms across spatial and temporal scales that are not achievable through traditional sampling [29]. Integration with machine learning algorithms will further improve accuracy and enable the detection of complex patterns in lake dynamics.

The emergence of Internet of Things (IoT)-based sensor networks allows real-time monitoring of in situ parameters such as dissolved oxygen and temperature. When combined with satellite observations and cloud-based platforms, these systems enable near-real-time assessment and early detection of ecological anomalies. Ecological models, including process-based tools such as (PCLake), simulate nutrient cycling, trophic interactions, and ecosystem responses to environmental drivers. Coupling these models with observational data through data assimilation techniques improves predictive capability and supports adaptive management under changing conditions.

Molecular and omics-based approaches, including environmental DNA (eDNA) and metabarcoding, are providing new insights into biodiversity and ecosystem health. These tools can detect early biological responses to environmental stress, often before changes are evident in physicochemical parameters, making them valuable for early warning systems. Early warning systems (EWS) are increasingly integrating multi-source data, including sensors, remote sensing, and climate forecasts, to predict events such as harmful algal blooms and hypoxia. Advances in artificial intelligence and cloud computing are enhancing the speed and accuracy of these predictions, allowing proactive management responses.

Table 1: Summary of changes observed as a function of temperature

Indicator change	Observed changes	Refences
Lake surface decrease (Northern hemisphere)	~0.34 °C per decade	https://doi.org/10.1038/s43017-020-0067-5
Ice decrease (Northern Hemisphere)	28-31 days over 150 years	https://doi.org/10.1038/s43017-020-0067-5 https://doi.org/10.3390/w16192727
Dissolved oxygen decline (Since 1980)	5.5% surface & 18.6% deep	https://doi.org/10.1038/s41586-021-03550-y
Stratification duration	Weeks to months	https://doi.org/10.1038/s41467-021-22657-4
Eutrophication or systemization effect on blooms	Increased frequency and intensity	https://doi.org/10.3390/w17213108

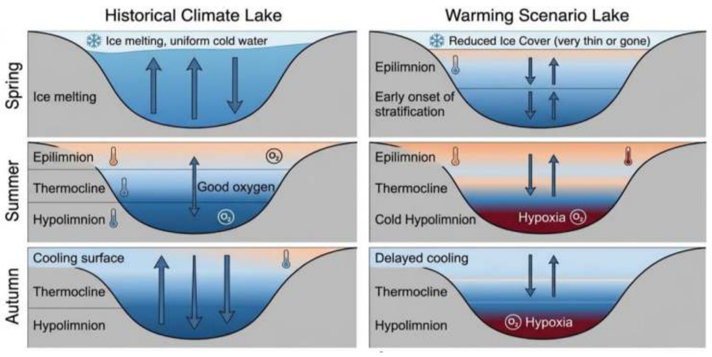

Figure 1: Schematic representation of lake thermal stratification under historical and warming conditions

The schematic shows changes in epilimnion, thermocline (metalimnion), and hypolimnion structure, showing increased surface warming, prolonged stratification, and reduced ice cover under warming scenarios.

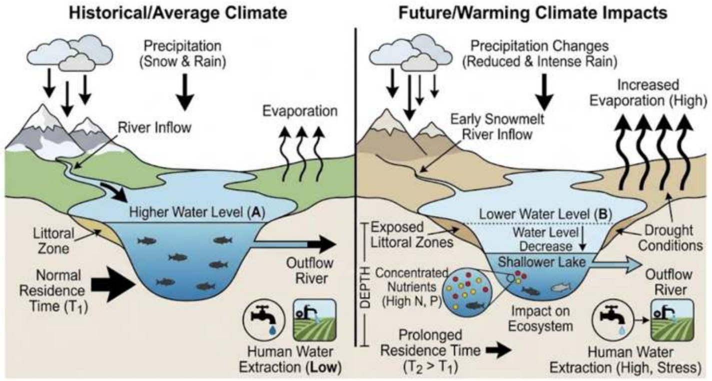

Figure 2: Conceptual cross-section illustrating the influence of hydroclimatic variability on lake water balance

The figure shows key hydrological components, including inflows (river discharge and surface runoff), precipitation, and outflows, along with processes such as evaporation and evapotranspiration. Alterations in rainfall patterns, earlier snowmelt, and drought conditions modify water inputs and residence time, leading to fluctuations in lake water levels. These changes are reflected in the exposure of littoral zones, concentration of nutrients in shallow regions, and shifts in hydrological connectivity. Human water extraction for domestic, agricultural, and industrial use is also depicted as an additional pressure influencing lake water balance.

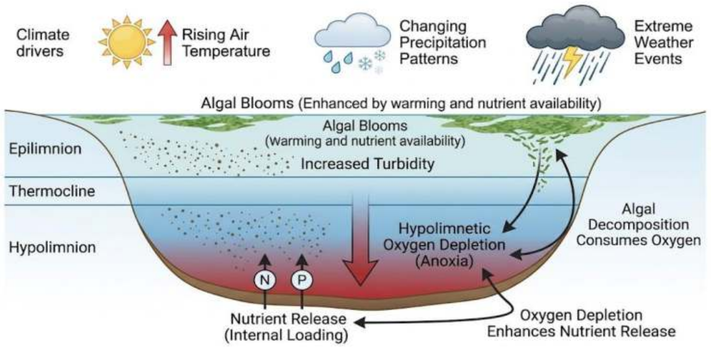

Figure 3: Conceptual diagram showing how hydroclimatic variability alters lake water balance components

Changes in precipitation, evaporation, runoff, and snowmelt influence inflows, outflows, and water residence time. The figure shows water level fluctuations, exposure of littoral zones, and nutrient concentration in shallow systems, along with human water extraction pressures affecting lake hydrology.

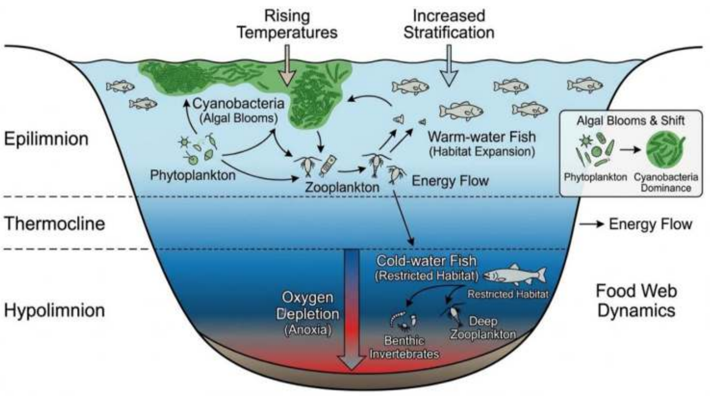

Figure 4: Schematic representation of changes in lake biodiversity and trophic interactions

Thermal stratification and oxygen gradients alter habitat availability, restricting cold-water species and favouring warm-water and tolerant taxa. The figure shows shifts in phytoplankton and zooplankton communities, increased cyanobacterial dominance, and simplified food web structure with reduced energy transfer efficiency across trophic levels.

Conclusions

Lake thermal structure and mixing dynamics are highly sensitive to climate variability and act as central controls on ecosystem functioning. Rising temperatures, altered wind regimes, shifting precipitation patterns, and reduced ice cover are collectively intensifying stratification, prolonging its duration, and weakening vertical mixing. These changes disrupt oxygen distribution, enhance nutrient accumulation in deeper waters, and alter the timing and extent of seasonal turnover. As a result, fundamental physical processes are being restructured, with cascading impacts on water quality, biological productivity, and ecosystem stability. Understanding and monitoring these evolving thermal dynamics is therefore critical for predicting future lake responses and for developing effective management and adaptation strategies under a changing climate.

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