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## Climate Change Impacts on Freshwater Ecosystems: Emerging Challenges and Adaptation Strategies

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### ABSTRACT

Water quality, temperature, flow regime, and mixing/stratification dynamics all have a significant impact on the biological structure of freshwater ecosystems. These systems are therefore among the most vulnerable to climate change. Rivers, lakes, wetlands, and groundwater-dependent habitats are examples of freshwater ecosystems. Climate change is changing inland waters through increased hydro-climatic extremes (droughts and floods), heatwaves, altered seasonality of precipitation and runoff, and warming (2015–2025). The effects of these modifications on salinization, dissolved oxygen, nutrient cycle, and harmful algal blooms are extensive. Lakes are increasingly viewed as climate sentinels due to their consistent physical responses, which include warmer surface waters, earlier and longer stratification seasons, and shorter ice durations. Hypoxia, internal nutrient loading, and a higher likelihood of cyanobacterial blooms can result from these alterations. Rivers and streams are impacted by warming channel waters, reduced summer baseflows in many places, more intense high-flow events, and an increasing predominance of extremes over mean trends. These factors then have an effect on habitat availability, connectivity, and contaminant concentrations. Climate change is a "threat multiplier," intensifying the effects of pre-existing pressures such as invasive species, habitat fragmentation, and nutrient pollution, and often triggering linear and threshold reactions, according to recent evaluations. Exposure to increasing maximum water temperatures is a major hazard pathway for freshwater fishes globally, and tracking the climate is challenging due to dispersal constraints in fragmented river networks. This review synthesizes adaptation strategies, such as restoration of connectivity, rehabilitation of riparian and floodplain areas, protection of climate refugia, co-management of water and quality, adaptive governance supported by improved monitoring, and environmental flows, and critically compares findings across ecosystem types and taxa from basin to site scales. It also highlights research gaps and uncertainties (such as attribution in multi-stressor contexts, thresholds, and small-water monitoring). Adaptation should be designed for extremes and cumulative pressures in addition to average changes.

### Introduction

Freshwater habitats not only provide an extraordinarily high rate of biodiversity in comparison to their area, but they also provide essential ecosystem services such as the provision of drinking water, irrigation, fisheries, hydropower management, nitrogen cycling, recreation, and flood buffering. Due to a variety of factors, including habitat loss, altered flows, pollution, overexploitation, and biological invasions, freshwater biodiversity losses continue to be among the greatest in the biosphere (Reid *et al.*, 2019; Tickner *et al.*, 2020). Additionally, these factors have contributed to the loss of freshwater biodiversity. According to the Intergovernmental Panel on Climate Change (IPCC), the rapidly increasing stress caused by climate change is causing changes in the thermal and hydrological templates that influence biological communities, biogeochemical processes, and the effectiveness of ecosystems. Regime shifts (such as stable hypoxia or persistent cyanobacterial bloom states) are more likely to occur, and historical baselines for management are less reliable, according to research that views climate change as an amplifier of current threats, specifically eutrophication, fragmentation, and water abstraction (Reid *et al.*, 2019; Woolway *et*

*al.*, 2022). This research was conducted by Reid *et al.*, 2019. Conventional methods of water resource management, which typically rely on historical data to forecast future hydrological variability and biological reactions, are being put to the test by this "non-stationarity" (IPCC, 2022). It is essential to take into consideration the fact that global synthesis indicates that freshwater fish are especially susceptible to extinction. This is due to the fact that, in contrast to many marine and terrestrial species, freshwater fish are vulnerable to climate change as a result of rising maximum water temperatures. Furthermore, their dispersal is restricted by the topology of river networks and barriers, which makes it difficult to monitor their climate change (Barbarossa *et al.*, 2021). Lakes are suitable climatic forcing sentinels because of the observable physical changes that they undergo, including as changes in ice phenology and the length of stratification (Woolway *et al.*, 2022). These changes have an impact on oxygen dynamics, bloom risk, and the loss of cold-water habitat.

**Objectives-** In the beginning, it provides a summary of the most important findings from research that was conducted between the years 2015 and 2025 focused on climate change and its effects on

freshwater ecosystems. The second thing that it does is compare and contrast the ways in which different types of water bodies, such as rivers, lakes, wetlands, and groundwater-linked systems, react to these particular influences. Thirdly, it identifies areas where there is either insufficient research or lack of clarity. (IPCC, 2022; Reid *et al.*, 2019; Tickner *et al.*, 2020) The evaluation arrives at its conclusion by analyzing the many adaptation alternatives that have the potential to enhance the resilience of these systems to the accumulation of stresses and the increasing severity of extremes.

#### **A Critical Analysis of the Literature**

How habitat models are evolving, the mechanisms that are involved, and the ongoing outcomes of global warming and heat waves are discussed. There are a number of ways in which warming can have an impact on freshwater ecosystems. These include changes in phenology, decreased solubility of dissolved oxygen, altered interactions between species, and direct physiological stress (metabolism, growth, and reproduction). In recent years, research has increasingly emphasized the ecological significance of heat extremes such as heatwaves and hot droughts, particularly in shallow streams and during low-flow periods when thermal buffering is at its weakest (IPCC, 2022; Johnson *et al.*, 2024). This is especially true in situations where the stream is shallow and when rainfall is low.

During compound low-flow/high-temperature episodes, river warming can cause localized death and a shift in thermal niches in rivers and streams. This can occur when the temperature is especially high. A recent assessment of the literature on river warming highlights the relationship between warming and common management stressors. This interaction is underlined in the following sentence. This analysis focuses on both direct and indirect consequences, including pollution, hypoxia, and a worsening of eutrophication (Johnson *et al.*, 2024). Direct effects include heat stress and changed life-history timing, while indirect effects include pollution and hypoxia. According to Johnson *et al.* (2024) and the Intergovernmental Panel on Climate Change (2022), these correlations are significant because a similar increase in temperature can have big consequences in rivers that are heavily abstracted or nutrient-enriched, whereas it can only have small effects in clean, well-shaded systems.

In lakes and reservoirs, rising temperatures raise the probability of deep-water hypoxia, internal nutrient loading, and bloom formation. This is especially true for cyanobacterial blooms, which thrive in warm, stable water. Additionally, rising temperatures make stratification more noticeable and last for a longer period of time (Woolway *et al.*, 2022). They also lessen the amount of times that mixing occurs. Shorter ice cover and longer stratified seasons have been directly associated with a number of cascade effects, including warmer summer temperatures, altered mixing and water levels, declines in dissolved oxygen, increased likelihood of cyanobacterial blooms, and loss of habitat for native cold-water fisheries, according to a major synthesis (Woolway *et al.*, 2022). This was discovered by Woolway *et al.*, 2022.

According to a thorough analysis, all types of systems exhibit substantial warming signals, but various reaction pathways are responsible for the warming behavior. For instance, rivers typically experience phenological shifts and habitat compression as a consequence of warming, whereas lakes display stratification-oxygen-bloom cascades (Johnson *et al.*, 2024; Woolway *et al.*, 2022). These findings were published in their respective studies. Both the Intergovernmental Panel on Climate Change (2022) and Woolway *et al.* (2022) emphasize the significance of temperature management in rivers (shading, groundwater connectivity, flow) and stratification/oxygen management in lakes (nutrient control, mixing regimes, oxygen protection) as independent but complementary adaptation aims.

Recent shifts in the hydrology, including new patterns of precipitation, the severity of drought and floods, and the links between these phenomena

It is the hydrological regime that serves as the master variable that determines the quantity and quality of habitat, the shape of the channel, the link between floodplains, and the frequency of disturbances. Hydrology is impacted by climate change because it changes the patterns of precipitation, evapotranspiration, snowmelt timing, as well as the frequency and severity of severe events (IPCC, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), many ecological systems are affected not only by yearly mean flow but also by seasonality and extremes.

According to Thompson *et al.*'s 2021, a global evaluation of the potential for ecological change in large river basins as a result of climate change has found possible threats to river ecosystems from temperature extremes and changing flow patterns. These risks have the ability to affect ecological integrity on a grand scale.

**Species and flow extremes-** It is important to note that different worldwide estimates place differing emphasis on the relative impact of temperature and flow extremes, and that different species react differently to variations in flow. An investigation on about 11,500 different species of river fish was carried out by Barbarossa *et al.* (2021) and published in Nature Communications. According to the findings of the study, the most significant impact on freshwater fish is caused by climate-related increases in maximum water temperature. On the other hand, amplified extreme flow conditions are less of a global problem, despite the fact that they might still be hazardous in certain regions for certain circumstances. Despite the fact that it is significant, this result ought to be interpreted with caution because, in many catchments, flow risk may be underestimated. This is due to the fact that global models do not take into consideration local hydrological extremes and smaller streams that are extremely sensitive to changes in biological conditions (IPCC, 2022; Johnson *et al.*, 2024).

Wetlands and floodplains are subject to major influence from the hydroperiod as well as the magnitude of the frequency of floods. While climate-driven droughts have the potential to shorten hydroperiods, decrease productivity, and change the dynamics of carbon storage, catastrophic floods have the ability to rearrange ecosystems and discharge pollutants and nutrients (IPCC, 2022). Wetlands are systems that are at thresholds, where even a tiny amount of drying out can result in dramatic shifts in the composition of communities or perhaps a complete transition to a different state, according to an increasing number of research (in accordance with the Intergovernmental Panel on Climate Change, 2022).

It is well known that the effects of hydrology are made worse by the construction of infrastructure such as dams, levees, and diversions, as well as abstraction of water. According to Reid *et al.* (2019) and Tickner *et al.* (2020), the combined influence of these factors on low-flow stress, reduced refugia availability, and constraints on recolonization following disturbances may have the potential to cause a reduction in adaptive capabilities.

Pollutants, saltwater intrusion, eutrophication synergy, and oxygen depletion are some of the factors that have an impact on the quality of water.

The loss of oxygen is a significant mechanism that is tied to climate, water quality, and hypoxia. Heat decreases the solubility of oxygen, which may lead to an increase in respiration, while stratification makes it more difficult for species that live in the deep ocean to continuously replenish their oxygen supply. A decrease in dissolved oxygen (DO) in lakes is a key result of longer stratification and less mixing, according to Woolway *et al.* (2022). This is stated in the study that was conducted by Woolway *et al.*, 2022. According to Johnson *et al.* (2024), rivers may be more susceptible to death during times of heat and drought because of the lower reaeration and greater biochemical oxygen demand impacts that are brought about by low flows and high temperatures.

Many people are beginning to see the multiplicative effects that eutrophication, climate change, and nutrient enrichment have on the environment. According to Woolway *et al.* (2022) and the Intergovernmental Panel on Climate Change (2022), cyanobacteria have the ability to thrive in settings that are warmer and more

stratified, which can lengthen bloom endurance. In contrast, droughts have the ability to extend the residence duration of nutrients and concentrate them, whereas excessive rains might result in the production of nutrient pulses. Rather than being a single variable, the dynamics of cyanobacterial blooms are affected by a number of different variables, including temperature, light, the stability of stratification, and the availability of nutrients (Song *et al.*, 2023).

After using satellite data to indicate that cyanobacterial blooms were developing as a result of climate change, a recent study by Li *et al.* (2025) advised including synergistic climatic impacts in control approaches. This was done after the researchers obtained evidence that cyanobacterial blooms were growing. In light of this, the growing body of research supporting the warming-bloom connection is strengthened. The findings are consistent with broader studies that have stressed the risk of blooms in warmer, more nutrient-rich oceans (Song *et al.*, 2023; Woolway *et al.*, 2022). Despite the fact that the findings are case-specific, they are consistent with these bigger evaluations.

Freshwater salinization is one of the new or worsening challenges to aquatic ecosystems, according to Reid *et al.* (2019), who note the growing significance of novel contaminants, engineered nanomaterials, microplastics, and light/noise pollution as interacting pressures in these systems. They also identify freshwater salinization as one of the risks to aquatic ecosystems. Researchers should think about how climate change is altering contaminant movement, transformation, and exposure through diverse hydrological and temperature regimes rather than focussing on a single pollutant (Reid *et al.*, 2019; IPCC, 2022).

Various responses to biodiversity, including openness, adaptability, vulnerability, and restrictions

The assessment of the vulnerability of freshwater fish has been advanced by the incorporation of conditions such as climate exposure, dispersal restrictions, and characteristics. Barbarossa *et al.* (2021) claim that maximum temperature rises dominate global risk pathways, and that many species may be subjected to much more extreme weather in a warmer world than the one we currently inhabit (Barbarossa *et al.*, 2021). As a result, maximum temperature increases are a major contributor to global warming. (Reid *et al.*, 2019; Tickner *et al.*, 2020) Research suggests that freshwater taxa may be especially susceptible to precarious situations in which dispersal paths are restricted due to network structure and artificial barriers.

Because of the fact that many freshwater populations are already under stress, the potential effects of both new and existing threats are significantly more severe than they would otherwise be. A total of twelve new or significantly increasing dangers have been found by Reid *et al.* (2019). These hazards include freshwater salinization, microplastics, rising hydropower, toxic algal blooms, climate change, cumulative stressors, and novel toxins. As a consequence of this, the consequences of climate change frequently amplify the effects of systems whose resilience has already been compromised (Reid *et al.*, 2019).

The lake synthesis brings attention to the loss of cold-water fishing habitat that is caused by warming temperatures and growing stratification shifts (Woolway *et al.*, 2022). This is accomplished by tying physical changes to fisheries and social effects. The IPCC WGII reports that ecological ramifications frequently evolve into direct dangers to human well-being, such as water security and fishery livelihoods, are supported by this new evidence, which lends credence to the thesis that has been made by the IPCC for a long time (IPCC, 2022).

Uneven evidence across taxa is a significant deficiency that has to be tackled. Evidence on plankton, microbiological processes, amphibians, and macroinvertebrates is sometimes limited to individual sites, in contrast to fish databases, which provide large-scale syntheses of the data. This taxonomic bias makes it difficult to make generalizations about ecosystems, particularly when it comes

to changes in food webs and biogeochemical feedbacks (Reid *et al.*, 2019; IPCC, 2022).

A "threat multiplier" for climate change is characterised by the accumulation of stressors over time and the occurrence of nonlinear reactions.

Interactions between climate change and other factors, which frequently result in non-linear or threshold reactions, intensify the effects of climate change. Recent studies (Reid *et al.*, 2019; IPCC, 2022) have uncovered a crucial and all-encompassing discovery related to climate change. The following are the three distinct applications of multipliers:

Warming and eutrophication both increase the likelihood of hypoxia and cyanobacteria dominance, particularly in areas that get a considerable amount of fertilizer inputs (Woolway *et al.*, 2022; Song *et al.*, 2023).

According to Johnson *et al.* (2024) and the Intergovernmental Panel on Climate Change (2022), the combination of pollution and drought increases the risk of acute mortality. This is due to the concentration of pollutants and nutrients in low flows, as well as the drop in oxygen levels.

This is due to the fact that barriers limit the dispersal that is necessary for climate tracking (Barbarossa *et al.*, 2021; Tickner *et al.*, 2020). Thus, the chance of local extinction is increased as a result of both warming and fragmentation.

It has been argued by Reid *et al.* (2019) and Tickner *et al.* (2020) that efforts to adapt to climate change will not be successful if they just focus on climate change. The use of land, connectivity, the control of exploitation, and the quality of water should be the primary areas of concentration instead.

#### **That which is being investigated**

#### **Strategies for flexibility, gaps in knowledge, and issues that will arise in the future**

Worries for the future (signal for the years 2015–2025): extremes will be in control. Complex occurrences, such as the escalation of heatwaves and the occurrence of hot droughts, have the capacity to overcome environmental resistance and bring about changes in regime. Strategies for management that place an emphasis on average changes run the danger of underestimating the impacts that are actually experienced (IPCC, 2022; Johnson *et al.*, 2024).

Complexity in governance and non-stationarity in the management of water distribution and infrastructure: climate change raises questions about the concept of stationarity and causes conflicts between the goals of various initiatives, including but not limited to irrigation, hydropower, flood control, and biodiversity. Despite the fact that it acknowledges the existence of limitations and difficulties, the Intergovernmental Panel on Climate Change (IPCC) World Greenhouse Gas Index (WGII) places a strong emphasis on the necessity of equitable governance and the existence of adaptation strategies that are both practical and efficient (IPCC, 2022).

A growing number of synthesis and mechanistic reviews (Song *et al.*, 2023; Woolway *et al.*, 2022) have revealed that there is a substantial relationship between stratification, warming, and the possibility for blooms, which puts both water security and public health in jeopardy. Bloom occurrences, which are an adaptation problem caused by excessive salinity, have a direct influence on aquatic life, recreational activities, and the quality of drinking water (IPCC, 2022).

An absence of data and monitoring is present. The availability of long-term data is limited in many vulnerable locations. Additionally, the dynamics of tiny streams and headwaters, which are frequently significant refugia, may be overlooked by global datasets (Johnson *et al.*, 2024; IPCC, 2022).

#### **The shortcomings of the research and the criteria for the methodology**

Further development of more robust research designs is required in order to differentiate climatic signals from infrastructure, nutrient inputs, and changes in land use. This calls for the utilization of integrated models, paired catchments, and designs that incorporate

both before-and-after and control-impact elements. The significance of this cannot be overstated, especially in light of the growing number of cumulative stressors that have been discovered (Reid *et al.*, 2019).

The conversion of wetland areas, persistent blooms, and prolonged hypoxia are all examples of regime changes that are frequently triggered by thresholds and early warning systems. Woolway *et al.* (2022) and Song *et al.* (2023) found that despite the fact that synthesis studies have brought to light the dangers, there are still very few early warning systems and prediction indicators that can be relied upon.

It is possible that global vulnerability models (such as fish risk) do not take into consideration local extremes, channel complexity, and headwater dynamics, despite the fact that these factors are important for prioritization (Barbarossa *et al.*, 2021; Johnson *et al.*, 2024). This is because of a scale mismatch. It is necessary to fill a significant void in order to establish a connection between basin-scale decision models and global screening.

The effectiveness of adaptation has been demonstrated by the fact that some treatments have received a great deal of praise without being subjected to sufficient testing against ecological outcomes (such as the persistence of biodiversity, the frequency of blooms, or resilience markers). According to Tickner *et al.*'s research from 2020, the "Emergency Recovery Plan" does feature a stringent action framework; nonetheless, additional evidence demonstrating its effectiveness in a variety of situations is required.

keeping a close eye out for fresh developments and patterns. EDNA, high-frequency sensors, and remote sensing are examples of new technologies that have the potential to enhance detection and attribution. However, there are still issues that need to be addressed regarding standardization and performance evaluation, as stated by Sahu *et al.* (2023) and Çevik *et al.* (2025).

#### **Implementation of change management strategies supported by research**

Protecting ecological services and habitat requirements in the face of changing hydrology is the most frequently prioritized adaptation for rivers, and climate-smart allocation is an essential component of this adaptation. According to Tickner *et al.* (2020), one of the primary goals of the Emergency Recovery Plan is to increase environmental flows in an effort to halt the reduction in the biodiversity of freshwater ecosystems. In light of recent methodological work, e-flow methodologies are being improved under climate restrictions and with limited data. This highlights the necessity of flexible targets that are able to account for non-stationary conditions and extremes (Leone *et al.*, 2024). An evaluation of environmental flows that is more comprehensive places an emphasis on the ecological implications of shifting flows, the significance of proper flow regimes for the preservation of ecosystem integrity, and the development of novel concepts (Wu *et al.*, 2023).

Point of criticality: Instead of striving to replicate historical averages, electronic flows ought to be planned for extremes on a more regular basis. In this way, drought refugia will be protected, and ecologically significant pulses, such as floodplain inundation, will be ensured whenever it is possible (IPCC, 2022; Tickner *et al.*, 2020).

#### **Facilitating the restoration of connectivity while protecting climate refuges**

Increasing adaptive capacity directly through the promotion of dispersal and recolonization is accomplished by restoring connection, which includes removing impediments, strengthening fish passage, and bypassing channels. Given that there is much data from all over the world that links fish risk to heat extremes and dispersal restrictions in river networks, this is of the utmost importance (Barbarossa *et al.*, 2021). According to Tickner *et al.*'s 2020 research, one of the six primary goals of the Emergency Recovery Plan is to restore and preserve the river link.

At the same time, protecting climate refugia is a "high return" strategy: wetlands that retain hydroperiods, spring-fed reaches,

groundwater-buffering tributaries, and deep lake zones with adequate oxygen can provide resilience against warming and hydrologic variability (IPCC, 2022; Johnson *et al.*, 2024).

#### **Restoration of the ecosystems of the river, watershed, and floodplain environment**

By lowering peak stream temperatures through shading, reforestation and the restoration of buffers along rivers can diminish the climate-eutrophication synergy (Johnson *et al.*, 2024; Woolway *et al.*, 2022). This is accomplished by limiting the supply of nutrients and sediment, enhancing the complexity of habitats and the stability of banks, and increasing the availability of habitats. According to the Intergovernmental Panel on Climate Change (IPCC), reestablishing floodplains has the potential to boost biodiversity, enhance water storage, reduce flood damage, and enhance drought resistance by diversifying ecosystems and refilling groundwater.

The most important realization is that, despite the degree of uncertainty, interventions to lower nutrient loads and improve habitat quality yield advantages that are "no regrets" since climate change exacerbates preexisting stresses (IPCC, 2022; Reid *et al.*, 2019).

#### **Management of lakes and reservoirs with the goal of minimizing the occurrence of blooms and maintaining enough oxygen levels**

According to the literature on lakes, adaptation must take into account the cascades of stratification, oxygenization, and blooming. Woolway *et al.* (2022) state that longer stratification seasons typically lead to oxygen depletion and an increase in the possibility of cyanobacterial blooms. This is the conclusion that draws from their research. The significance of biological traits and environmental elements that are impacted by warming and stratification stability in the formation of cyanobacterial blooms has been further highlighted by mechanistic studies (Song *et al.*, 2023). There has been an increase in the amount of study conducted in recent years on the topic of how lake heatwaves alter bloom dynamics and ecological risk (Duan *et al.*, 2024).

An all-encompassing plan (backed up by tangible evidence):

The reduction of external nutrient inputs (at the watershed scale);

**Whenever you can, take control of your internal stressors;**

It is important to carry out high-frequency and early warning monitoring (with the help of sensors and remote sensing), and to carefully examine ecological trade-offs when considering selective mixing and aeration (Woolway *et al.*, 2022; Song *et al.*, 2023).

In addition to electronic DNA and remote sensing, sensors for adaptive monitoring and decision support are also available.

Improving one's ability to recognize ecological responses and extremes is absolutely necessary in order to successfully adapt to climate change. In recent times, electronic DNA has been recognized as a feasible alternative to invasive biodiversity surveys.

This alternative has the potential to be beneficial in identifying species that are uncommon, invasive, or have a low population (Sahu *et al.*, 2023; Çevik *et al.*, 2025). There are several factors that influence the performance of eDNA, including hydrology, transport, degradation, and sampling design. Therefore, in order to provide reliable decision support, it is necessary to conduct systematic evaluations and adhere to standard methods (Çevik *et al.*, 2025). To capture extremes and support prompt response, the use of high-frequency sensors for temperature and oxygen as well as remote sensing for surface temperature and bloom proxies is becoming increasingly important. This is in line with the International Panel on Climate Change's (IPCC) emphasis on adaptation planning in the face of changing risk profiles (IPCC, 2022).

Sustainable development refers to the process of coordinating individual actions with the goal of restoring biodiversity and adapting to a changing climate.

The Emergency Recovery Plan provides a framework that is both practical and integrative. This framework includes the implementation of environmental flows, the enhancement of water quality, the protection and restoration of habitats, the management of exploitation, the prevention and control of invasive species, and

the reestablishment of connectivity (Tickner *et al.*, 2020). According to the Intergovernmental Panel on Climate Change (IPCC), adaptation is possible; however, it is limited by issues regarding equality, resources, and governance (IPCC, 2022; Reid *et al.*, 2019). This is in line with the "threat multiplier" idea that was presented by Reid *et al.* (2019). For effective governance, it is necessary to take a holistic approach to the adaptation of freshwater systems. It is of the utmost importance to prioritize efforts that promote resilience to extreme events and the cumulative repercussions of stress, and it is also essential to avoid program silos (IPCC, 2022; Tickner *et al.*, 2020).

#### Last but not least

The findings of studies carried out between the years 2015 and 2025 indicate that the effects of climate change are already being seen in freshwater ecosystems. A cascade of effects on water quality, which are typically made worse by fertilizer contamination and fragmentation, are the reasons of this phenomenon. Warming, changing hydrological regimes and a cascade of consequences are the causes of this phenomenon. The decline in ice cover, the longer stratification, the warmer surface waters connected to oxygen depletion, the bloom hazard, and the loss of cold-water habitats are all characteristics of the climatic change that is occurring in lakes. Fish vulnerability is directly linked to rising maximum water temperatures and fewer dispersal chances in fragmented river networks. Additionally, shifting seasonality and extremes are making rivers and wetlands more vulnerable to the effects of flooding and other environmental stresses. Rehabilitating floodplains and riparian zones, reducing nutrient inputs, controlling oxygen and bloom risks in lakes, strengthening adaptive governance with the assistance of contemporary monitoring, and putting climate-smart environmental flows into practice are the different adaptation strategies that have the most support from scientific research. In the future, research should focus on attribution in settings that contain many stressors, early warning systems, tiny rivers and headwaters that are not effectively monitored, and the necessity of conducting comprehensive regional assessments of the effectiveness of adaptation. In the future decades, it will be vital to develop solutions for extremes rather than simply implementing change in order to protect the biodiversity of freshwater ecosystems and ensure the security of water supplies.

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