

CLIMATE CHANGE AND FRESHWATER ZOOLOGY: ADAPTIVE RESPONSES OF AQUATIC ORGANISMS TO ENVIRONMENTAL STRESS

Dr. M.Abareethan¹, Dr.Nilanchala Sethy², Ramar Marimuthu³, Km Reshu⁴, Bikash Choudhury⁵, Dr. Smita Shukla^{6*}, Sanat Chandravanshi⁷

¹Associate Professor And Head, Department Of Zoology, Government Arts College (Autonomous), Periyar University, Salem -636007, Tamil Nadu, India, Email ID: abareethan@gmail.com, ORCID ID: 0000-0002-0069-1855, Scopus ID: 59968781600

²Assistant Professor, Department of Law, Lingaraj Law College A Constituent College of Berhampur University, Berhampur, Odisha, pin no;760010, Email ID: nila_llc@rediffmail.com

³Assistant Professor, PG Department of Biochemistry, Rev Jacob Memorial Christian College, Ambilikai Oddanchatram Dindigul Tamil Nadu India. ORCID ID: <http://orcid.org/0000-0003-3874-5238>, Email ID: ramareri@gmail.com

⁴Researcher, Department of Zoology, Babasaheb Bhimrao Ambedkar University, Lucknow , Uttar Pradesh, 226005
Email ID: reshu362026@gmail.com

⁵Research Scholar, Department of Zoology, Dhamma Dipa International Buddhist University, Email ID: bikashchoudhuryddibu@gmail.com

^{6*}Assistant Professor, Department of Zoology, College Swami Shraddhanand College Alipur, University of Delhi. ORCID ID: 0009-0004-8007-4022, Email ID: smitashukla1972@gmail.com

⁷Ph.D. Scholar, Department of Aquatic Animal Health, Faculty of Fishery Sciences, West Bengal University of Animal and Fishery Sciences (WBUAFS), West Bengal University of Animal and Fishery Sciences (WBUAFS). Email ID: chandravanshisnat97@gmail.com, ORCID ID: 0009-0000-1534-8139

ABSTRACT

Climate change has emerged as a major global environmental challenge affecting freshwater ecosystems and aquatic biodiversity through rising temperatures, altered hydrological cycles, acidification, salinity intrusion, eutrophication, and hypoxia. Freshwater organisms are particularly vulnerable to these environmental stressors because of their narrow physiological tolerance ranges and habitat specialization. This review critically synthesizes current scientific knowledge regarding the adaptive responses of freshwater aquatic organisms to climate-induced environmental stress. Relevant peer-reviewed studies published between 2010 and 2026 were systematically analyzed to evaluate physiological, behavioral, morphological, and genetic adaptation mechanisms across major freshwater taxa, including fish, amphibians, macroinvertebrates, mollusks, crustaceans, and zooplankton. The findings indicate that freshwater organisms exhibit diverse adaptive strategies such as heat shock protein production, osmoregulatory adjustments, antioxidant defense activation, migration shifts, altered reproductive timing, and developmental plasticity to cope with changing environmental conditions. However, the review also highlights that prolonged exposure to multiple interacting stressors may exceed the adaptive capacity of many species, leading to biodiversity decline, ecological imbalance, and reduced ecosystem resilience. Furthermore, the study emphasizes the importance of climate-resilient conservation planning, adaptive freshwater management, and long-term ecological monitoring. Emerging technologies including genomics, environmental DNA, and AI-based ecological modeling are identified as promising tools for improving biodiversity assessment and climate adaptation strategies in freshwater ecosystems.

KEYWORDS: Climate change, freshwater ecosystems, aquatic organisms, adaptive responses, biodiversity conservation

INTRODUCTION

Climate change is one of the most serious environmental issues impacting global ecosystems and biodiversity in the modern day. It involves long-term changes in temperature, precipitation, atmospheric composition and extreme climatic events that are primarily caused by anthropogenic factors, including deforestation, fossil fuel burning, industrialization and urbanization (Jaramillo & Mendoza-Ponce, 2022). Global warming trends and ecological disturbances are more intensified in terrestrial and aquatic environment due to the increasing concentration of greenhouse gases (Chowdhuri & Gupta, 2023). The small spatial scale of freshwater ecosystems and their high ecological sensitivity make them especially sensitive to these environmental changes, as suggested by current climate projections (Warziniack et al., 2022). Freshwater biodiversity and ecosystem stability is increasingly under threat globally due to rising temperatures, changing hydrological cycles, longer droughts, flooding events and declining water quality.

Freshwater ecosystems, such as rivers, lakes, wetlands, streams and ponds are essential to ecological balance and biological diversity. Although they cover only a small part of the Earth's surface, these ecosystems host a significant share of the aquatic biodiversity globally and are valuable biodiversity hotspots (Apostolaki et al., 2020). Freshwater organisms play a vital role in the functioning of the ecosystems in terms of nutrient cycling, trophic regulation, decomposition process and maintenance of the aquatic food web. Furthermore, freshwater systems serve as key sources of ecosystem services, including freshwater purification, irrigation, fisheries production, carbon sequestration and drinking water. Moreover, freshwater systems also support human livelihoods and sustainable development through various ecosystem services, including the provision of freshwater, purification, irrigation, fisheries production, carbon sequestration and drinking water.

Freshwater zoology has increasingly become a subject of scientific interest in the realm of climate change, due to the sensitivity of water organisms to changes in the environment. Freshwater species like fish, amphibians, macroinvertebrates, mollusks, crustaceans and zooplankton are often sensitive to climatic stressors, due to their narrow physiological tolerance ranges and specific habitat needs (Becker et al., 2018). Water temperature, oxygen levels, salinity, and hydrological conditions can affect the reproductive cycles, migrations, feedings, and interactions among species of freshwater systems. However, many aquatic organisms have adaptive responses in the form of physiological acclimatization, behavioural change, phenotypic plasticity and genetic adaptation to respond to environmental stress (Muccione et al., 2024). Although the field has seen a lot of research in recent years, this knowledge is still scattered and fragmented among ecological, physiological and conservation research. As a result, an integrative review of adaptive responses in freshwater organisms is needed to understand ecological resilience and develop effective conservation strategies for climate resilience as presented in Figure 1.

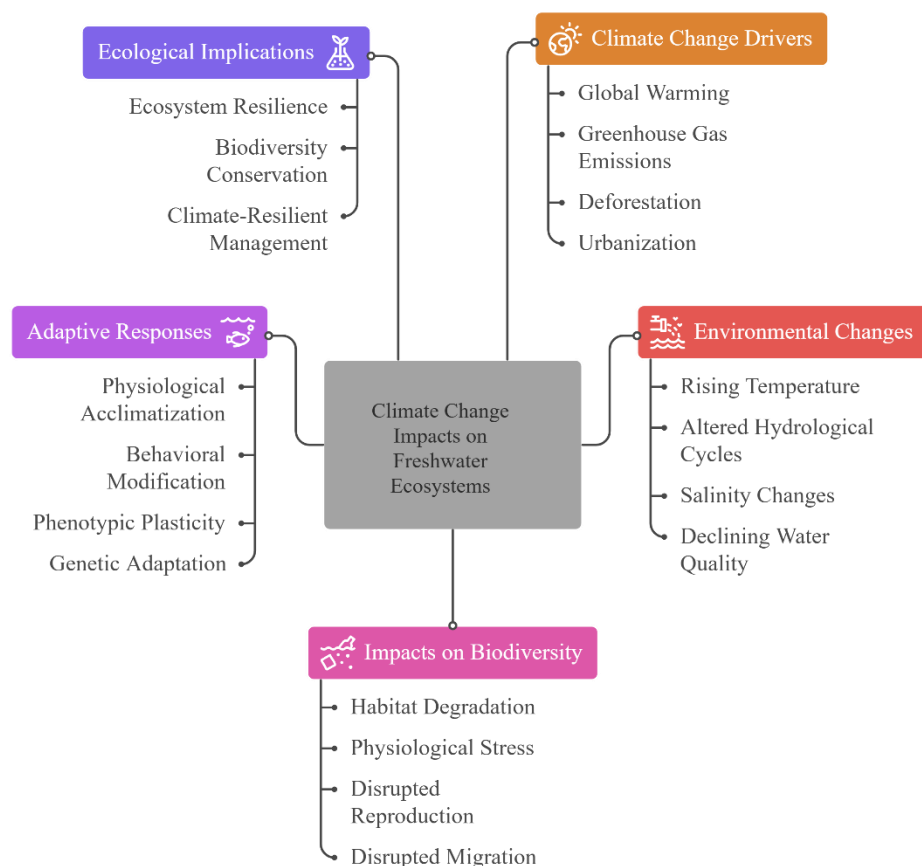


Figure 1: Conceptual Framework of Climate Change Impacts on Freshwater Ecosystems and Adaptive Responses of Aquatic Organisms

The figure illustrates the relationship between climate change drivers, environmental alterations, biodiversity impacts, adaptive responses of freshwater organisms, and ecological implications, highlighting how aquatic species respond to environmental stress and contribute to ecosystem resilience and climate-resilient freshwater conservation.

Objectives

1. To identify and evaluate the major climate-induced environmental stressors affecting freshwater aquatic organisms and ecosystems
2. To critically analyze the physiological, behavioral, morphological, and genetic adaptive responses of freshwater fauna to climate change
3. To assess the ecological and conservation implications of adaptive mechanisms for improving freshwater biodiversity resilience and climate-resilient ecosystem management

2. METHODOLOGY

This study employed a comprehensive systematic review approach following PRISMA 2020 guidelines to synthesize existing knowledge on the adaptive responses of freshwater aquatic organisms to climate-induced environmental stressors. Relevant peer-reviewed articles published between 2010 and 2026 were retrieved from major scientific databases including Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar using Boolean search combinations such as “climate change AND freshwater organisms,” “aquatic adaptation AND environmental stress,” and “thermal tolerance in freshwater fauna.” Studies were included if they focused on freshwater species and examined adaptive responses to stressors such as rising temperature, hypoxia, acidification, salinity changes, and hydrological variability, while marine-

only and non-peer-reviewed studies were excluded. Extracted data included taxonomic groups, environmental stressors, physiological and behavioral adaptations, ecological impacts, and conservation implications. The selected literature was critically evaluated for methodological quality and synthesized through thematic analysis to identify major adaptation patterns, resilience mechanisms, and ecological consequences across freshwater taxa.

3. RESULTS

3.1 Climate Change and Freshwater Ecosystems

Climate change has become a major force in driving ecological change in freshwater systems, and is modifying physical, chemical and biological properties of these systems. Climatic variations significantly affect the fresh water habitats as they are directly linked with the atmospheric temperature, precipitation pattern, and hydrological processes. The effects of global warming, changing rainfall patterns, acidification, salinity, eutrophication and interacting stress are growing and exacerbating environmental pressures on freshwater biodiversity and ecosystem function (Nimma et al., 2025). These climate-induced changes are now known to be a significant threat for aquatic organisms, ecological stability and sustainability of freshwater resources across the globe.

3.1.1 Rising Water Temperature

The first clear-cut effect of climate change in freshwater systems is an increased temperature of the water. Changes in atmospheric temperatures affect thermal regimes and result in significant changes in river, lake and reservoir ecosystems and hydrology. In freshwater systems, especially lakes and reservoirs, the changes in thermal stratification due to rising temperatures result in changes to nutrient distribution, oxygen availability, and aquatic productivity, which are driven by the temperature stratification (Azadi et al., 2021). Better thermal stratification will have less water mixing in the columns, which will limit oxygen transport deeper into the water column and make it more stressful for aquatic organisms. Further, due to climate change, the frequency and severity of freshwater heatwaves has increased. Excessive high temperatures over long periods of time can affect the physiology, reproductive cycles, feeding and metabolic activity of aquatic fauna. Hypoxic stress is also exacerbated in freshwater habitats under warmer water temperatures, as the dissolved oxygen will decline as the water warms. These changes pose a risk to temperature-sensitive organisms, particularly those that rely on cold waters for survival, such as fish, and oxygen-dependent aquatic life (Nimma et al., 2025).

3.1.2 Altered Hydrological Cycles

Climate change is significantly influencing global hydrological cycles by altering the distribution, frequency and intensity of precipitation, evaporation rates and processes of water distribution. Floods and droughts are occurring more often in freshwater systems because of variations in intensity and seasonal precipitation (Benestad et al., 2022). Flooding events can cause habitat destruction, sediment displacement, and nutrient overloading and prolonged droughts can cause a decrease in water availability, a decrease in aquatic habitat, and an increase in stress to the organisms. Fluctuations in streamflow and water-level alterations have a significant impact on freshwater ecological processes. A lower flow and decreasing water levels can lead to an increase in water temperature, salinity concentration, and the buildup of pollutants, which will reduce habitat quality. On the other hand, too much flooding could change the spawning sites, affect migration routes and displace aquatic species. These hydrological perturbations have direct impacts on the distribution of species, patterns of diversity and the capacity of freshwater ecosystems to resist stress.

3.1.3 Acidification and Water Chemistry Alterations

The effects of higher levels of CO₂ in the atmosphere include freshwater acidification via increased CO₂ dissolving into aquatic systems. This process reduces the pH and changes the water chemistry, which has an impact on water physiology and ecology of freshwater organisms (Hasler et al., 2018). Aquatic fauna are sensitive to acidification, even at low levels, affecting growth and reproduction, sensory behaviour and survival. Water chemistry changes caused by a changing climate also affect biogeochemical processes and nutrient cycling in freshwater environments. Changes in nutrient cycling may impact primary productivity, microbial processes, and trophozoology. Moreover, acidification can lead to enhanced mobilization and bioavailability of heavy metals and of other toxic compounds from sediments to the water column, which can further worsen toxicity risks to freshwater organisms and lead to biodiversity losses.

3.1.4 Salinity Intrusion and Osmotic Stress

Sea-level rise and climate change impacts, as well as reduced inflow of freshwater, are driving increased salinity intrusion into freshwater ecosystems. Salinization in fresh water is becoming an ever-growing ecological problem, due to the fact that numerous freshwater species are sensitive to salinity changes (Tadić et al., 2024). Higher salinity creates physical stress due to ionization imbalance and osmotic stress. Inland aquatic habitats can be greatly affected by salinity intrusion, which can alter species composition, decrease biodiversity, and allow salt-tolerant organisms to spread. Under salinity stress, fresh water organisms have to expend extra energy to maintain internal homeostasis. Continuous osmotic stress may affect growth, reproduction, immune function and survival, especially in stenohaline organisms that are sensitive to salinity.

3.1.5 Eutrophication and Hypoxia

Freshwater eutrophication processes are accelerated by climate change, which brings about enhanced nutrient run-off, higher temperatures, and a different hydrology. Under warming conditions, nutrient enrichment, especially the excessive nitrogen and phosphorus input, leads to the growth of algal blooms (Dai et al., 2023). Harmful algal blooms lower water quality, diminish light levels and throw off the balance of aquatic food webs.

Excessive algal biomass decomposes, using up significant amounts of dissolved oxygen, in fresh water systems. Aquatic organisms can't survive or reproduce in "dead zones" that are caused by oxygen depletion. Fish, amphibians, macroinvertebrates and other oxygen dependent species are adversely affected by hypoxia because it interferes with their respiration, metabolism and ecological relationships. Eutrophication and hypoxia are thus among major climate threats to freshwater biodiversity and ecosystem functioning.

3.1.6 Synergistic Effects of Multiple Stressors

The impact of multiple interacting stressors on fresh water ecosystems is increasing, with each stressor contributing to the degradation of the ecosystem, and each stressor operating on its own, increasing the likelihood of further degradation. Pollution, habitat fragmentation, overexploitation and invasive species are often associated with climate change and can exacerbate environmental stress to freshwater organisms (McComb & Cushman, 2020). These stress factors can occur together and often they are more detrimental than when they occur separately.

The synergies of climate change and pollution may increase the toxicity of pollutants and decrease organismal tolerance to environmental stress. Construction of dams, land-use change and hydrologic alteration due to dams and changes in land use prevent species from migrating and exchanging genes, reducing their adaptive capacity. Warming also could allow invasive species to invade freshwater ecosystems, which could compete with native fish for resources and habitat space. The combined effect of these stressors may cause biodiversity loss, change of community structure, and disruption of ecosystem processes and functions, endangering ecological resilience and long-term sustainability as displayed in Table 1.

Table 1. Major Climate Change-Induced Stressors and Their Impacts on Freshwater Ecosystems and Aquatic Organisms

Climate Change Factor	Major Environmental Changes	Impacts on Freshwater Ecosystems	Biological Effects on Aquatic Organisms	Key Reference
Rising Water Temperature	Thermal stratification, heatwaves, reduced dissolved oxygen	Altered water chemistry and oxygen dynamics	Metabolic stress, reduced reproduction, species mortality	Azadi et al. (2021)
Altered Hydrological Cycles	Floods, droughts, fluctuating streamflow	Habitat instability and water scarcity	Migration disruption, habitat loss, population decline	Benestad et al. (2022)
Acidification and Water Chemistry Alterations	Lower pH, nutrient imbalance, heavy metal mobilization	Changes in biogeochemical cycling	Impaired growth, reproduction, and survival	Hasler et al. (2018)
Salinity Intrusion and Osmotic Stress	Freshwater salinization	Altered ionic balance and habitat quality	Osmoregulatory stress and reduced biodiversity	Tadić et al. (2024)
Eutrophication and Hypoxia	Nutrient enrichment, algal blooms, oxygen depletion	Formation of hypoxic “dead zones”	Respiratory stress and aquatic mortality	Dai et al. (2023)
Synergistic Multiple Stressors	Climate change interactions with pollution and invasive species	Ecosystem degradation and fragmentation	Reduced resilience and accelerated biodiversity loss	McComb & Cushman (2020)

3.2 Overview of Selected Literature

A comprehensive survey of the peer-reviewed literature found a significant number of studies reporting on the impacts of climate change on freshwater ecosystems and aquatic organisms in various geographical areas of the world, such as North America, Europe, Asia and Australia. The literature reviewed encompassed ecological, physiological, behavioural and conservation studies related to the effects of environmental stressors on freshwater biodiversity. The major freshwater groups studied were fish, amphibians, macroinvertebrates, zooplankton, molluscs and crustaceans. The majority of studies highlighted the compounding effects of climate change stressors on freshwater ecosystem structure, species interactions and ecological resilience (Birk et al., 2020).

3.2.1 Major Climate-Induced Stressors Identified

All the climate change related stressors were found to be common factors which have caused alteration in freshwater ecosystems. One of the key stressors was water temperature which led to thermal stress, decreased dissolved oxygen, changes in metabolism and heat wave-induced ecosystem instability. Reproductive success, species distribution and physiological performance of temperature-sensitive organisms were negatively impacted by elevated temperatures (Jackson et al., 2021). Habitat degradation and fragmentation was also caused by hydrological changes, such as more droughts, flooding, and changing streamflow patterns. Drought caused water shortages and increased salinity, and flooding caused ecological imbalance and problems with spawning. Moreover, freshwater organisms were subjected to high stress due to changes in water chemistry, including acidification, saltwater intrusion, eutrophication, and hypoxia, which disturbed their physiological reactions, nutrient cycles and oxygen levels.

3.2.2 Physiological Adaptive Responses

Freshwater organisms were found to have a variety of physiological adaptations responding to the environmental stress caused by the climate change. Thermal tolerance mechanisms consisted of the synthesis of heat shock proteins (HSPs), which would stabilize proteins and preserve the integrity of cellular structures in face of increased temperature. Energy use regulation under thermal stress conditions was also frequently reported, which can be considered as metabolic acclimatization. Aquatic organisms under hypoxic conditions were shown to have respiratory adaptations and activation of hypoxia-induced factors (HIFs), which increased the efficiency of oxygen utilization and increased survival under

hypoxic conditions (Lee et al., 2020). Several species also adapted to anaerobic metabolic pathways as a reaction to oxygen depletion (Chaillou 2018). Under salinity stress, the organisms balanced their internal homeostasis and ionic concentration using specific ion regulation mechanisms that were found to be of special importance. Also, resistance to environmental stressors/stress induced oxidative damage was increased through improved antioxidant defense systems (Ozturk et al., 2021; Wang et al., 2022).

3.2.3 Behavioral Adaptations

Behavioural adaptations were important ways in which the freshwater animals adapted to their rapidly changing environment. Increased temperatures and habitat degradation led to migration and range shifts toward cooler or more favorable habitat in many aquatic species. The feeding behaviors and foraging tactics were commonly altered and observed under stressful environmental conditions. Reproductive seasonality was also affected by climate variability, with some species showing breeding season shifts related to hydrological and temperature variations. In addition, changes in habitat selection, such as migration toward oxygenated microhabitats and habitat concealment, were found to be significant responses to environmental stress (Cameron & Schoenfeld, 2018).

3.3.3 Morphological and Evolutionary Responses

Morphological and evolutionary changes in freshwater species were significant due to stress caused by climate change. Reduction in body size was common in warming and is probably due to metabolic constraints and resource limitations. Developmental plasticity allowed organisms to adapt the growth pattern and physiological characteristics to environmental changes (Freschet et al., 2018). Furthermore, there was growing recognition of genetic adaptation and epigenetic responses as important long-term mechanisms contributing to ecological resilience and species survival. Freshwater organisms further increased their adaptive capacity through evolutionary interactions of microbial symbiosis and ecological adaptations to changing climate (Moran et al., 2019).

3.3.4 Taxa-Specific Vulnerability and Resilience

The review showed significant differences across freshwater taxa in their climate resilience. There was also a high degree of thermal tolerance variation among fish species, with a majority of cold-water species moving to higher latitudes and elevations as temperatures rose. The amphibians were found to be very vulnerable because they require water for respiration and are more susceptible to diseases with shifting climate changes. Community composition and sensitivity to decreased oxygen, increased acidity, and increased temperature were pronounced in macroinvertebrates and zooplankton. In the mollusks, there was impairment of shell formation under acidified conditions, while in the crustaceans, different levels of salinity adaptation were shown by osmoregulatory adjustments. But, in many fish species, multiple exposures over long periods of time had a negative impact on survival and reproductive performance.

3.3.5 Ecological Consequences

Water-related environmental stress caused by climate change had strong impacts on freshwater ecosystems. Habitat and species interactions changes led to changes in aquatic food webs and trophic dynamics, which led to reduced ecological stability. Loss of biodiversity, especially specialised and endemic freshwater species was increasingly observed. Climate change also enabled species replacement and invasive species expansion, thus changing community composition and ecosystem processes. Moreover, the synergies of several stressors on freshwater biodiversity significantly influenced the functioning of the whole ecosystem, such as nutrient cycling, productivity and ecological resilience (Birk et al., 2020).

3.8 Conservation and Management Findings

The reviewed studies highlighted the need to implement conservation and adaptive management practices that are resilient to climate change to safeguard freshwater biodiversity in the face of environmental change. Wetland rehabilitation, riparian vegetation recovery and ecological flow regimes were recognized as effective habitat restoration techniques to enhance ecosystem resilience. Furthermore, it was recommended that biodiversity monitoring frameworks that incorporate long-term ecological assessment and multi-stressor analysis be developed to support biodiversity conservation planning and climate adaptation activities (Guerra et al., 2019). The results underscored the need for the interdisciplinary, evidence-based, and ecosystem monitoring approaches to reduce the impacts of climate change on freshwater ecosystems and aquatic organisms.

DISCUSSION

Climate adaptation is increasingly known to be one of the most critical challenges to freshwater ecosystems and aquatic biodiversity globally. The results of this review confirm that warming, hydrological variability, acidification, salinity intrusion, eutrophication, and hypoxia all put a significant amount of stress on freshwater organisms and processes. Freshwater species showed a wide spectrum of adaptive responses such as physiological acclimatization, behavioural changes, morphological plasticity, and genetic adaptation, which would be vital for their survival when the environment changes. Mechanisms like production of heat shock proteins, osmoregulation, activation of antioxidant defence and hypoxia tolerance promote metabolic regulation and stability of cells under environmental stress. Likewise, behaviours such as migration, habitat selection, behaviour change, and changes in reproductive timing offer short-term ecological benefits that minimize exposure to bad conditions (Cameron & Schoenfeld, 2018). While these adaptive responses are biologically significant as they are important to ecological resilience and species persistence, the review also shows that the adaptive ability of many freshwater species may not be adequate in the rapid and long-term climate change scenarios (Radchuk et al., 2019).

The review also uncovered significant differences in the resilience of freshwater taxa. Thermal tolerance variability and distributional shifts toward cooler habitats were shown to be relatively greater adaptive flexibility in fish species, while one of the most vulnerable groups were the amphibians due to their moisture-dependent physiology and susceptibility to disease. Macroinvertebrates and zooplankton were very sensitive to oxygen depletion, acidification and thermal stress, leading to important changes in community composition and changes in trophic dynamics. Under salinity stress, mollusks

and crustaceans showed osmoregulatory responses, but exposure to several stressors for extended periods of time decreased the growth and reproductive success of these organisms. The results are consistent with previous studies that have shown that physiological tolerance limits, specialization of habitat, dispersal power, and ecological interactions are important factors affecting the resilience of species. The review also underscores how more and more developmental plasticity, microbial symbiosis, and evolutionary adaptation are playing a role in sustaining freshwater resilience in the face of climate stress (Moran et al., 2019). However, other evidence is emerging that adaptation may not be sufficient to address the speed and complexity of environmental change.

The effect of climatic stress on the environment is far-reaching and may be irreversible. Changes in habitat, species interactions and trophic relationships can cause aquatic food webs to become unstable, leading to a decrease in ecosystem productivity and contributing to the loss of biodiversity. The results indicate that in many freshwater ecosystems, adaptation may be insufficient to keep ecological processes stable and that thresholds may have been passed. Increased warming, habitat fragmentation, salinization and oxygen depletion could promote the spread of invasive species, species replacement, and nutrient cycling processes. These ecological changes pose risks to freshwater ecosystem services such as fisheries production, water purification and water resource sustainability. Therefore, there is an urgent need to plan the use and conservation of freshwater in a way that is climate resilient, to reduce biodiversity loss and ecosystem degradation. Conservation strategies based on adaptive management, with a focus on habitat restoration, ecological flow maintenance, protection of wetlands and the reduction of anthropogenic stressors, are gaining recognition as effective conservation strategies (Thomann et al., 2020). Finally, planning for conservation that is climate-informed should also include ecological refugia, habitat connections, and biodiversity monitoring frameworks that are necessary for ecosystem resilience over the long-term (Stralberg et al., 2020).

The use of emerging technologies such as genomics, transcriptomics, environmental DNA (eDNA), and ecological modeling using artificial intelligence offers prospects for advancing freshwater climate adaptation studies and biodiversity analysis. The use of long-term ecological monitoring systems that combine remote sensing and automatic environmental analysis can further improve the understanding of the response of freshwater ecosystems to future climates. Although many advances have been made in freshwater climate research, there are significant gaps, especially for tropical freshwater ecosystems, long-term ecological data, and multi-stressor experiments. Furthermore, publication bias, geographical imbalance, taxonomic constraints and differences in the methods used to conduct the studies may have affected the presentation of results in this review. Despite this, the current review reveals a generalized overview of the adaptive reactions of freshwater organisms to environmental stress caused by climatic change and underlines the importance of a multidisciplinary ecosystem, physiology, molecular, and conservation strategy for sustainability of freshwater biodiversity in the changing global climate.

CONCLUSION

Freshwater ecosystems and the variety of organisms they sustain are increasingly threatened by climate change. The combined effects of increasing temperature, changes in the water cycle, acidification, salinity intrusion, eutrophication and hypoxia impair the ecological stability and biodiversity of freshwater environments. The present review shows that there are a variety of adaptive responses (physiological acclimatizations, behavioral modifications, morphological plasticities, genetic adaptations) that are exhibited by freshwater organisms and that play a key role in improving survival in an environmental stress. Yet the ability to adapt to the climate change and a host of compounding stresses is curtailed for many species. Some freshwater taxa are more resilient than others and this reflects the sensitivity of more specialised, and temperature-sensitive, species, such as the amphibians and macroinvertebrates, and cold-water fish. Ecological changes caused by climate change add to biodiversity loss, food web disruption, invasive species spread and decreasing ecosystem services. The review highlights the critical need to develop measures that will conserve freshwater resources in the face of climate change, to adaptively manage ecosystems and to establish long-term monitoring frameworks for biodiversity in order to prevent ecological degradation in the future. Additionally, the incorporation of new technologies, like genomics, environmental DNA, and AI-guided ecological modelling can enhance the predictive power and conservation planning. However, interdisciplinary research and evidence-based policy interventions are crucial to increase the resilience of freshwater ecosystems and to maintain the sustainability of freshwater biodiversity throughout the world under different climate scenarios.

REFERENCES

1. Apostolaki, S., Akinsete, E., Koundouri, P., & Samartzis, P. (2020). Freshwater: The importance of freshwater for providing ecosystem services. *Encyclopedia of the World's biomes*, 71-79.
2. Azadi, F., Ashofteh, P. S., & Chu, X. (2021). Evaluation of the effects of climate change on thermal stratification of reservoirs. *Sustainable Cities and Society*, 66, 102531.
3. Becker, L. A., Crichigno, S. A., & Cussac, V. E. (2018). Climate change impacts on freshwater fishes: a Patagonian perspective. *Hydrobiologia*, 816(1), 21-38.
4. Benestad, R. E., Lussana, C., Lutz, J., Dobler, A., Landgren, O., Haugen, J. E., ... & Parding, K. M. (2022). Global hydro-climatological indicators and changes in the global hydrological cycle and rainfall patterns. *PLoS Climate*, 1(5), e0000029.
5. Birk, S., Chapman, D., Carvalho, L., Spears, B. M., Andersen, H. E., Argillier, C., ... & Hering, D. (2020). Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. *Nature Ecology & Evolution*, 4(8), 1060-1068.
6. Cameron, H. A., & Schoenfeld, T. J. (2018). Behavioral and structural adaptations to stress. *Frontiers in neuroendocrinology*, 49, 106-113.

7. Chaillou, T. (2018). Skeletal muscle fiber type in hypoxia: adaptation to high-altitude exposure and under conditions of pathological hypoxia. *Frontiers in physiology*, 9, 1450.
8. Chowdhuri, A., & Gupta, C. K. (2023). Gauging the assessment of some anthropogenic factors driving climate-change. *Current World Environment*, 18(2), 614.
9. Dai, M., Zhao, Y., Chai, F., Chen, M., Chen, N., Chen, Y., ... & Zhang, Z. (2023). Persistent eutrophication and hypoxia in the coastal ocean. *Cambridge Prisms: Coastal Futures*, 1, e19.
10. Freschet, G. T., Violle, C., Bourget, M. Y., Scherer-Lorenzen, M., & Fort, F. (2018). Allocation, morphology, physiology, architecture: The multiple facets of plant above-and below-ground responses to resource stress. *New Phytologist*, 219(4), 1338-1352.
11. Guerra, C. A., Pendleton, L., Drakou, E. G., Proença, V., Appeltans, W., Domingos, T., ... & Pereira, H. M. (2019). Finding the essential: Improving conservation monitoring across scales. *Global Ecology and Conservation*, 18, e00601.
12. Ha, T. P., Dieperink, C., Otter, H. S., & Hoekstra, P. (2018). Governance conditions for adaptive freshwater management in the Vietnamese Mekong Delta. *Journal of Hydrology*, 557, 116-127.
13. Han, S., Xing, Z., Jiang, H., Li, W., & Huang, W. (2021). Biological adaptive mechanisms displayed by a freshwater plant to live in aquatic and terrestrial environments. *Environmental and Experimental Botany*, 191, 104623.
14. Hasler, C. T., Jeffrey, J. D., Schneider, E. V., Hannan, K. D., Tix, J. A., & Suski, C. D. (2018). Biological consequences of weak acidification caused by elevated carbon dioxide in freshwater ecosystems. *Hydrobiologia*, 806(1), 1-12.
15. Jackson, M. C., Pawar, S., & Woodward, G. (2021). The temporal dynamics of multiple stressor effects: from individuals to ecosystems. *Trends in ecology & evolution*, 36(5), 402-410.
16. Jaramillo, A., & Mendoza-Ponce, A. (2022). Climate change overview. In *The Impact of Climate Change on Fungal Diseases* (pp. 1-18). Cham: Springer International Publishing.
17. Lee, P., Chandel, N. S., & Simon, M. C. (2020). Cellular adaptation to hypoxia through hypoxia inducible factors and beyond. *Nature reviews Molecular cell biology*, 21(5), 268-283.
18. Madliger, C. L., Love, O. P., Hultine, K. R., & Cooke, S. J. (2018). The conservation physiology toolbox: status and opportunities. *Conservation Physiology*, 6(1), coy029.
19. McComb, B. C., & Cushman, S. A. (2020). Synergistic effects of pervasive stressors on ecosystems and biodiversity. *Frontiers in Ecology and Evolution*, 8, 569997.
20. Moran, N. A., Ochman, H., & Hammer, T. J. (2019). Evolutionary and ecological consequences of gut microbial communities. *Annual review of ecology, evolution, and systematics*, 50(1), 451-475.
21. Mortoja, M. G., & Yigitcanlar, T. (2020). Local drivers of anthropogenic climate change: Quantifying the impact through a remote sensing approach in Brisbane. *Remote Sensing*, 12(14), 2270.
22. Muccione, V., Haasnoot, M., Alexander, P., Bednar-Friedl, B., Biesbroek, R., Georgopoulou, E., ... & Schmidt, D. N. (2024). Adaptation pathways for effective responses to climate change risks. *Wiley Interdisciplinary Reviews: Climate Change*, 15(4), e883.
23. Narimisa, M. R., & Narimisa, M. R. (2018). Climate change and global warming overview; assessing climate change and global warming in local scale. *Revista Publicando*, 5(14 (2)), 570-580.
24. Nimma, D., Devi, O. R., Laishram, B., Ramesh, J. V. N., Boddupalli, S., Ayyasamy, R., ... & Arabi, A. (2025). Implications of climate change on freshwater ecosystems and their biodiversity. *Desalination and Water Treatment*, 321, 100889.
25. Ozturk, M., Turkyilmaz Unal, B., García-Caparrós, P., Khursheed, A., Gul, A., & Hasanuzzaman, M. (2021). Osmoregulation and its actions during the drought stress in plants. *Physiologia plantarum*, 172(2), 1321-1335.
26. Perera, H., Jayawardana, C., & Chandrajith, R. (2024). Freshwater salinisation: unravelling causes, adaptive mechanisms, ecological impacts, and management strategies. *Environmental Monitoring and Assessment*, 196(12), 1195.
27. Radchuk, V., Reed, T., Teplitsky, C., van de Pol, M., Charmantier, A., Hassall, C., ... & Kramer-Schadt, S. (2019). Adaptive responses of animals to climate change are most likely insufficient. *Nature communications*, 10(1), 3109.
28. Stralberg, D., Carroll, C., & Nielsen, S. E. (2020). Toward a climate-informed North American protected areas network: Incorporating climate-change refugia and corridors in conservation planning. *Conservation Letters*, 13(4), e12712.
29. Tadić, J., Dumičić, G., Veršić Bratinčević, M., Vitko, S., & Radić Brkanac, S. (2024). Challenges of salinity intrusion and drought stress on Olive tree cultivation on Mljet Island. *Plants*, 13(18), 2549.
30. Thomann, J. A., Werner, A. D., Irvine, D. J., & Currell, M. J. (2020). Adaptive management in groundwater planning and development: A review of theory and applications. *Journal of Hydrology*, 586, 124871.
31. Wang, X., Yao, Q., Zhang, D. M., Lei, X. Y., Wang, S., Wan, J. W., ... & Guo, Z. X. (2022). Effects of acute salinity stress on osmoregulation, antioxidant capacity and physiological metabolism of female Chinese mitten crabs (*Eriocheir sinensis*). *Aquaculture*, 552, 737989.
32. Warziniack, T., Arabi, M., Brown, T. C., Froemke, P., Ghosh, R., Rasmussen, S., & Swartzentruber, R. (2022). Projections of freshwater use in the United States under climate change. *Earth's Future*, 10(2), e2021EF002222.