ISSN: 2978-3801

Journal of Global Warming and Climate Change

SCIENTIFIC Research and Community

Review Article

Open Access

Climate Change Responses in Freshwater Ecosystems

Juliet Akudo Mbabie[1] and Francis Olawale Abulude[2*]

[1]Chemistry Advanced Research Centre, Sheda Science and Technology Complex, Abuja, Nigeria

[2]Environmental and Sustainable Research Group, Science and Education Development Institute, Akure, Ondo State, Nigeria

ABSTRACT

Climate change is increasing disturbance in freshwater ecosystems and modifying hydrological processes, ecological stability, and ecosystem functioning. Intensified droughts, changed rainfall patterns, heatwaves, and flooding events are altering river, wetland, lake, and estuarine systems over several spatial scales. Although there is abundant literature documenting ecological damage from climatic variability, little attention has been given to the mechanisms by which ecological stability of freshwater ecosystems is maintained under ongoing climatic disruption. The purpose of this review is to bring together current understanding of the relationships between climate-driven hydrological change and freshwater ecosystems. In particular, emphasis is placed on ecological thresholds, biodiversity buffering capacity, adaptive behavior, and governance mechanisms which promote ecosystem recovery from impacts. In the second half of the review, an integrated framework that links climatic influences with ecological impacts and adaptive pathways is proposed. Results suggest that connectivity, diversity of ecological functions, ecological memory and institutional fluidity can strongly promote ecosystem resilience. The long-term sustainability of freshwater ecosystems will ultimately depend on the capacity of their management regimes to respond to environmental variability, non-linear responses and increasing rates of change.

***Corresponding author**
Francis Olawale Abulude, Environmental and Sustainable Research Group, Science and Education Development Institute, Akure, Ondo State, Nigeria.

Received: June 06, 2026; **Accepted:** June 11, 2026; **Published:** June 20, 2026

Keywords: Climate Change, Freshwater Ecosystems, Hydrological Extremes, Resilience, Adaptive Governance, Ecological Thresholds

Introduction

The climate has been increasingly recognized as the most important determinant of the structure, function, and health of freshwater ecosystems [1]. Rising air temperatures, altered precipitation regimes, and an increase in extreme weather events are altering hydrological processes and challenging ecosystem stability and species diversity [2]. Despite their relatively small global surface area, freshwater ecosystems harbor a disproportionate share of biodiversity, playing key roles in ecosystem processes including nutrient cycling, fishery production, water purification, and flood regulation. Nevertheless, an accumulating body of evidence indicates that disturbances related to a changing climate increasingly threaten the thresholds of many aquatic ecosystems' adaptive capacities.

Many of the studies examining a changing climate have tended to focus on documenting the ecological degradation of freshwater systems, for example, see Sarhan and El-Ghani et al. [3,4]. Fewer studies have concentrated on the specific mechanisms that underpin ecosystem resistance and resilience following the disturbance of climatic variability. Resilience refers here not only to the ability of the system to withstand stresses, but also to its capacity to adapt and to re-organize to continue carrying out its essential functions following disturbance.

This review seeks to clarify the complex relationship between climate-driven hydrological extremes and the resilience of freshwater systems. Specifically, it addresses three core themes:

- The impact of climate-induced disturbances on freshwater ecosystems;
- The mechanisms through which system resilience may be strengthened; and
- The adaptation pathways through which ecological sustainability may be enhanced.
- 2. Climate Change and Hydrological Disturbance in Freshwater Ecosystems

Climate change affects freshwater systems through a series of interrelated hydrological impacts. Rising atmospheric temperatures accelerate the rate of evapotranspiration, modifying stream flow, and intensifying seasonal water deficits.

Increasing Water Temperature

Rising water temperature is one of the more consistent and significant impacts of climate change on freshwater ecosystems [5, 6]. Temperature increases in both ambient and surface waters directly affect the thermal structure of rivers, lakes, reservoirs, and wetlands and lead to dramatic changes in ecosystems. Higher temperatures can lower the dissolved oxygen content within the water column, which can stress and lead to the death of fish that require well-oxygenated conditions. The rate of metabolism, growth, reproductive success, and migratory ability of many species are strongly linked to their body temperature [7]. Certain species adapted to colder conditions may be unable to adapt to the higher temperatures, and their viable habitats are likely to shrink. Invasion and widespread occurrence of harmful algae and exotic species may be stimulated by higher water temperatures. Diseases are more prevalent among organisms that are exposed to thermal stress, and there can be substantial ecosystem production loss. Stratification in lakes is becoming more pronounced and is of longer duration, thus inhibiting the exchange of nutrients between layers of the water column. Increased temperatures also influence microbial processes and thereby have ecosystem-level consequences across various trophic levels [8, 9].

Altered Precipitation Regimes

Global climate change is influencing precipitation regimes at various scales by altering intensity, frequency, duration, and seasonality. Changes in precipitation significantly impact freshwater systems through alteration of water availability and connectivity of riverine, wetland, lake, and estuarine environments. Increased intense precipitation may trigger more frequent flooding, whereas decreased precipitation may lead to more prolonged periods of water shortage and drought [10]. These impacts affect species that have adapted to a consistent streamflow regime. Increased runoff and sediment load during high-intensity precipitation may degrade water quality through pollution. Reduced rainfall can lead to smaller stream flows and lower groundwater levels, causing loss of habitat and water scarcity. Alterations to seasonal rainfall can provide important ecological cues that are critical for reproduction, migration, and feeding of many aquatic species, and changes in their timing may lead to ecosystem-level dysfunction [11].

Extreme Climatic Events

Extreme climatic events such as floods, droughts, heatwaves, and storms are becoming more frequent and intense under changing climatic conditions. These events exert profound pressures on freshwater ecosystems by causing rapid environmental disturbances that exceed the adaptive capacity of many species. Floods can alter channel morphology, increase sediment deposition, and transport pollutants into aquatic habitats. Droughts reduce water volume, increase water temperature, and concentrate contaminants, thereby creating stressful conditions for aquatic organisms [12]. Heatwaves can trigger mass fish mortality events due to oxygen depletion and thermal stress. Repeated extreme events may disrupt food webs, alter species composition, and reduce biodiversity. Furthermore, ecosystem recovery between disturbances may become increasingly difficult as the interval between extreme events shortens. Such disturbances often interact with existing anthropogenic pressures, including pollution, land-use change, and water abstraction. Consequently, extreme climatic events are increasingly recognized as major drivers of ecosystem transformation and resilience loss in freshwater environments [9].

Table 1: Climate Drivers and Their Ecological Consequences

Climate driver	Hydrological impact	Ecological consequence
Rising temperature	Increased evaporation	Habitat contraction
Drought	Reduced stream discharge	Biodiversity decline
Extreme rainfall	Flood intensification	Sediment redistribution
Heat waves	Thermal stress	Fish mortality
Sea-level rise	Saltwater intrusion	Wetland degradation

Table 1 summarizes the direct impacts of major climatic drivers on freshwater ecosystem components. Increasing temperatures lead to enhanced evaporation and thus reduced water availability and aquatic habitat; falling stream discharge due to drought leads to decreases in connectivity and increases in inter-specific competition for habitat and resources; extreme rainfall events result in increased flooding and sediment transport leading to physical alteration of habitat structure and ecosystem processes; increased incidence of heatwaves cause thermal stress resulting in fish kills and changing species composition; sea level rise results in saltwater intrusion into coastal freshwater systems, threatening wetland habitat and decreasing freshwater biodiversity. The figure illustrates that many drivers can act in combination resulting in compounding ecosystem impacts. Impacts on productivity, diversity, nutrient cycling and the resilience of the system are therefore varied and complex. The information presented shows the importance of an integrated and preventative approach in managing for many pressures concurrently. The direct impacts of key climate drivers are crucial for adaptation and mitigation of climate change in freshwater ecosystems.

Ecological Thresholds and Regime Shifts

Ecological thresholds and regime shifts have been called some of the most important concepts in contemporary resilience theory as they explain abrupt, non-linear and often irreversible ecosystem change under steady environmental forcing. A threshold refers to a point where beyond a critical point small increments in environmental forcing cause disproportionately large ecological responses. Ecosystems before a threshold point appear quite stable while subject to increasing stress. Once threshold points are surpassed, the system often undergoes rapid change to a new state. Climate change is increasing the probability of exceeding freshwater ecological thresholds as it leads to warming temperatures, altering hydrologic regimes and increasing event intensity. Lake, river, wetland and estuary ecosystems are particularly vulnerable to climate change impacts due to their high sensitivity to alterations in quantity and quality of water. A lake subject to increasing nutrient loads and higher temperatures may tip from a clear water state where submersed aquatic vegetation dominates to a turbid, algae dominated state that limits both diversity and services and impacts water quality [13]. Recovering from regime shifts is not always an easy process as removing the initial disturbance does not guarantee a return to a previous state in systems where hysteresis is occurring. Hysteresis is when a system's response lags and does not follow the same path upon relaxation of a forcing, as the new ecosystem state is self-sustaining through feedback processes. As an example, algal dominated lakes often retain a degraded state with low submerged aquatic vegetation and high nutrients, despite a decrease in nutrient loads because existing biotic and abiotic conditions may maintain the algae dominated state. Hydrologic thresholds can lead to transformation between ecosystems as sustained drought may reduce vegetation coverage and soil moisture in wetland systems and promote transformation to arid conditions while sea level rise promotes saltwater intrusion and transformation of wetlands to brackish or saline systems, changing species composition, ecosystem function and habitat quality. Reduced flows and increased temperature can push aquatic organisms past physiological thresholds and cause loss of key species, leading to subsequent changes in food webs and ecosystem processes. Ecological thresholds thus illustrate that freshwater ecosystem change does not necessarily proceed at a steady, linear rate but rather it is characterized by critical points and non-linear dynamics. Research in the area of regime shifts therefore also focuses on predicting these critical threshold points and the possibility of detecting early warning signals, such as loss of variability, slowing recovery, and declining species diversity. Threshold based approaches offer effective means of climate change adaptation, ecosystem restoration and sustainable management of freshwater systems [9, 14, 15].

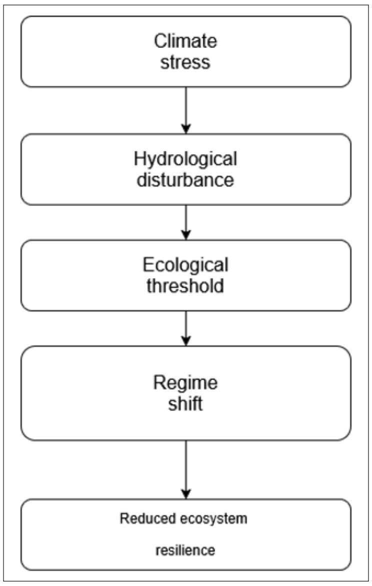

Figure 1: Conceptual Pathway of Climate-Induced Ecosystem Change

Climate disturbances and their influence on ecosystem change are shown conceptually in Figure 1. At the start of the conceptual framework, ecosystem change is driven by climate disturbances such as increasing temperature, changes in precipitation, and extreme climatic events. Hydrological process like streamflow, groundwater recharge, stream water temperature and frequency of flood is altered as the changes are introduced into the water systems. Environmental stress for ecosystem is increased as disturbances in hydrological process grow, affecting ecosystem diversity, productivity, and habitat. At first, there might be a certain resistance to regime shift using existing mechanisms of resistance. Continuous exposure to disturbance however, leads to the accumulation of ecological pressures. As ecological thresholds are crossed, the ecosystem may experience a sudden change to a new stable state regime shift-often with very different ecological structure and function-like lakes becoming eutrophic, wet lands becoming terrestrial dry land etc. After a regime shift, ecosystem service will generally decline and recovery will be more difficult. Resilience in this regard has limited capacity, where ecosystems are not able to cope with more than a certain degree of disturbances. For the sake of identifying regime shifts and the thresholds, the early warning signs must be identified so as to avoid it happening. Also, adaptive management practices should be conducted before the thresholds are crossed.

Mechanisms Underpinning Ecosystem Resilience

Biodiversity and Functional Redundancy

Biodiversity is arguably the cornerstone of ecosystem resilience because of its ability to support the resilience of an ecosystem against environmental disturbances. The concept of functional redundancy describes how species carry out equivalent functional processes and roles within the ecosystem and how it may contribute to the overall resilience of the ecosystem following disturbance event. If species is removed as a result of disturbance event, then remaining functional species are able to compensate for lost function and maintain ecosystem processes. This significantly lowers the possibility of an ecosystem collapse following the disturbance events and reduces reliance on a single species or function. Besides this functional diversity contributes to ecosystem productivity and nutritional cycles, stability of food webs and other processes. Additionally, different responses of species provide response diversity and may allow an ecosystem to adapt to the changes in environment. Hence, biodiversity in a natural environment can be thought of as an insurance against an unpredictable future. Research demonstrates a positive correlation between species richness and the ability of ecosystems to recover following droughts, floods and heatwaves. Biodiversity therefore can be regarded as climate adaptation tool in a similar way to other strategies and adaptation techniques [16].

Hydrological Connectivity

Hydrological connectivity is defined as the capacity of water, nutrient, sediment, and organism flow among and between aquatic environments. Such flow links lakes, wetlands, floodplains, rivers and groundwater into a networked structure that is essential for ecosystem functions like species migration, recovery and gene flow after disturbances, nutrient transport and productivity. The flow in these aquatic systems is significantly affected by anthropogenic modifications of river channels, by building dams and water abstraction, thus impacting ecosystem connectivity and overall resilience. Creation and protection of corridors connecting different elements of an aquatic network ensures better functioning and species mobility throughout these ecosystems. It is a key component of adaptation strategies since it improves the species capacity to recover from extreme climatic events and it sustains vital ecological processes throughout these systems.

Ecological Memory

Ecological memory refers to the tendency of the ecosystem to retain biological legacies, like dormant seed and microorganism populations, existing vegetation or physical structures, from previous conditions that enable ecosystems to respond to future disturbances. As an example, dormant seeds and plant propagules ensure immediate regrowth following fire or flood events and also serve as an insurance policy against unpredictable climatic events and as a tool for the restoration of damaged or degraded ecosystems. Memory of ecological responses to previous stress can lead to ecosystem stability; yet chronic stress may also deplete the ecological memory and lower the ecosystem's resistance to repeated disturbances. An ecosystem with long and persistent memory would provide immediate source for the reestablishment of communities; however prolonged disturbance can lead to the erosion of this memory, making the recovery slow.

Adaptive Capacity

Adaptive capacity defines an ability of an ecosystem to change in order to survive an environment that is changing and it encompasses many related concepts: degree of reorganization after disturbance, plasticity of components within an ecosystem or capability to adapt to change without significant structural degradation or functional collapse. The latter includes the ability of the system to reconfigure itself into a more or less drastically alternative stable state while maintaining its primary ecological functions. Ecological memory and biodiversity can significantly improve the adaptive capacity of a natural system. Enhanced capacity can result from well-established networks of connectivity; human driven land management and resource extraction activities can also modify and impact a system's ability to adapt.

Table 2: Key Drivers of Freshwater Ecosystem Resilience

Resilience mechanism	Ecological role	Expected outcome
Biodiversity	The capacity of a site to remain functional.	Faster recovery
Connectivity	Movement of species to another place.	Increased adaptation
Ecological memory	Assistance in the recovery.	Reduced collapse risk
Adaptive governance	The ability to be flexible and adapt.	Long-term sustainability

Four underlying mechanisms sustaining freshwater ecosystems were highlighted in Table 2. Biodiversity ensures ecosystem persistence through functional redundancy and response diversity, Connectivity promotes processes such as migration, recolonization, nutrient cycling and therefore, adaptive responses. Ecological memory, sustains biological and structural heritage through disturbance; Adaptive Governance builds the institutional flexibility required to adapt to uncertain changes. These processes all operate at various spatial and temporal scales and ultimately their interactions determine the capability of ecosystems to resist, recover and adapt to climate-change related disturbances. As seen from Table 2, it is not a single process which defines the persistence of an ecosystem, but rather the complex interplay of social and ecological processes that determines the ecosystem response to disturbances. As such the proposed strategies would aim at enhancing biodiversity conservation, hydrological connectivity, ecological memory and the capacity of governance institutions; failure to do so will increase susceptibility of the ecosystem to extreme climatic events in the future.

Adaptive Governance and Climate Response

Traditional water management assumes a stable climate and thus proposes fixed ways of dealing with hydrological uncertainty; increasing changes to our water systems necessitate adaptive governance mechanisms.

Ecosystem-Based Adaptation

Ecosystem-based adaptation measures use biological diversity and ecosystem functions to enhance the resilience of both human and ecological systems to the effects of climate change and has become an important part of international climate adaptation policies. Using healthy ecosystems can decrease the vulnerability of human communities and ecosystem functions, whilst promoting co-benefits to social systems. For instance, the restoration of wetlands can support hydrological regulation, water purification, and carbon sequestration. Riparian vegetation helps to reinforce river banks, decreases river flow, thereby promoting river flow regulation and also decreasing water temperature through shading. Floodplain restoration increases water storage capacity of catchments and thereby decreasing the flood risk of downstream areas. Ecosystem-based adaptation offers more cost-effective solutions to engineered climate adaptation alternatives while conserving biological diversity. It increases ecosystem resilience and human well-being alike [17].

Integrated Watershed Management

Integrated watershed management involves coordinated planning and management of water, land and ecosystem resources within a watershed. Ecosystem health is understood to depend on events in the upstream watershed. A successful watershed management plan requires participation from multiple stakeholders and sectorial groups, helping to tackle problems of water scarcity, pollution, habitat degradation and impacts from climate change, as well as aiming to balance economic and social objectives. Watershed level management planning also aids to maintain the hydrological connectivity of an ecosystem and promotes a sustainable way of managing water and land resources; the approach has been considered as an integral part of climate change adaptation of freshwater ecosystems.

Climate-Informed Monitoring

Climate-informed monitoring combines climatic scenarios with ecologically-oriented indicators and new technologies for environmental monitoring. Innovations in remote sensing, Geographic Information Systems, Artificial Intelligence and sensors have improved our ability to detect environmental change. Monitoring programmes contribute important data about water quality, biodiversity, hydrological variations and ecosystem health. Early detection of environmental stress through monitoring enables targeted intervention in the management plan to avoid critical thresholds [18]. Time-series data of monitoring provides valuable insight into the ecosystem responses to hydrological change and climatic variability. This knowledge facilitates informed decision-making and adaptive management strategies.

Integrated Resilience Framework

This study proposes an integrated framework composed of:

Climate Drivers

Climate drivers represent the first link in a causal chain that establishes climate change impacts on freshwater ecosystems. These drivers may include increase in global temperature, altered precipitation patterns and increase in evapotranspiration as well as frequency and intensity of extreme climate events. Global warming increases water temperatures and water loss from streams, lakes, wetlands and reservoirs, leading to reduced water availability in many parts of the world. Changing precipitation patterns also result in varied hydrological regimes due to varying magnitudes of rainfall within a season and increasing alternations between floods and drought in certain watersheds. Stream flow can become reduced due to premature snow melt in mountains with increasing temperatures and decreased infiltration as a result of long-term droughts which leads to decreased recharge of ground water. Increased temperatures also raise the demand for water for vegetation and exacerbate water shortage in vulnerable catchments. Coastal freshwater systems also face the risk of saline intrusion due to sea level rise. In sum, these changes modify the distribution and availability of water resources, thereby impacting their quality and quantity as well as leading to diverse forms of freshwater ecosystem impacts and transformations. It is thus critical to develop better understanding of the relation between climate drivers and hydrological regime for predictive purposes and for developing adequate management measures [9-11].

Hydrological Disturbance

Climate-change driven alterations of the hydrological regime affect the ecosystem by reshaping the habitat, disrupting life cycles, or modifying biological production. Reduced flow levels under drought conditions can limit the availability of habitat to aquatic species and result in high concentrations of nutrients, thus placing stress on the system. Increased river discharge can cause flooding that alters river morphology and the physical landscape or physically washes away vegetation from riparian banks. Availability of adequate flow can critically determine reproductive success and distribution of several aquatic species as well as influencing species' foraging patterns. Alteration of hydrological conditions is shown to be an influential factor in controlling species metabolic rate, body growth, and reproductive outcomes. Restricted connectivity among aquatic habitats may affect species genetics and thus make it susceptible to varying environmental conditions. The amount and timing of nutrient inputs and removal within the system can be altered by changes to the hydrological regime, including nutrient loading in the river systems and in the wetlands. Reduced wetland water flow may make it impossible to maintain the specialized flora and fauna species in a wetland. The relationship among various biotic factors such as predation, competition, or symbiosis may also shift, especially when conditions transcend the threshold of species' biological capabilities to adjust; the aggregation of all these responses may lead to ecosystem transformations [9-19].

Ecological Response

Biological responses to climatic and hydrological disturbances provide the underlying mechanisms that either determine if a system will recover, persist or transform. Such responses are developed through a suite of biotic and abiotic processes that contribute to system resilience and adaptive capacity, including evolutionary and life history changes [20]. The behavior, distribution and life history patterns of individuals or populations may be altered by environmental change. Range shifts and life history strategies adjust in relation to changing conditions and biological clocks. Biological processes in species such as behavioral plasticity and reproduction play a critical role in a species' response to ecological disturbance, whereby certain taxa shift distribution and time their life cycles to better match new environmental conditions. Functional redundancy by various species performing similar functions in the ecosystem ensures continued services under variable conditions. Interactions between species promote ecological reorganization of the system rather than total ecosystem failure. Habitat heterogeneity increases persistence under disturbance through creating niche refuges and supporting species resilience. Genetic diversity strengthens adaptation potential by ensuring populations with necessary tolerances are likely to survive and maintain breeding populations. Ecological memory, such as a seed bank and residual populations of key species help maintain the integrity of the system through disturbance events and contribute to post-disturbance recovery. In short, these are processes that decrease vulnerability, facilitate persistence of systems during extreme events and contribute to maintenance of ecological functions [16-21].

Resilience Mechanisms

These mechanisms help in designing adaptable governance systems that can support sustainable management of ecosystems. Governance adaptation involves changing institutions, policies and management strategies to meet dynamic environmental changes and advancements in knowledge. Information of the ecosystem features like diversity, connectivity, ecological memory, and adaptiveness assist managers to pinpoint features that strengthens the resilience of the system and these features should be conserved [22]. For instance, due to the important role played by connectivity in keeping species in movement, barrier like dams would be eliminated or reduced. Ecological memory would foster conservation of remnant sites where the population can use for recovery. Instead of applying rigorous management methods, adaptive governance aims at establishing institutions which can cope with the unpredictable situations and changing environments. Local and traditional knowledge coupled with social acceptance are vital components which would enhance the acceptance of the management actions while participatory monitoring would assist in adapting strategies over time and improving efficiency of the governance. By correlating management practices with resilience attributes, governance can avert vulnerability and promote long-term sustainability of freshwater ecosystems [23, 24].

Governance Adaptation

The identification of resilience mechanisms provides valuable insights into the design of adaptive governance systems capable of sustaining ecosystem management. Governance adaptation consists of altering policies, institutions and management methods in response to environmental changes and the development of scientific understanding. The data available on the diversity, connectivity, ecological memory and adaptive capacity of a system assist decision-makers to identify features that reinforce ecosystem resilience. Management approaches should be adapted to maintain or bolster these qualities. Thus, the removal of a dam which hinder the movement of animals may be considered due to the ecological significance of species connectivity. Similarly, ecological memory would result in the preservation of remnant habitats for populations and facilitate re-establishment. Rather than strict management actions adaptive governance stresses flexible institutions which can deal with uncertainty and changing environments. A greater emphasis on stakeholder participation in governance is important to acquire local knowledge and improve social acceptance for management decisions, whereas monitoring systems contribute by providing feedback information which can be utilized to make alterations to the strategies on a continual basis. Governance, consequently, requires an integration of knowledge of ecosystems and their intrinsic capacities in institutions to make management effective. When management actions are geared towards resilience features governance can decrease the susceptibility of the system to changes and augment the long-term viability of freshwater ecosystem.

Ecosystem Outcomes

The role of adaptive governance is that it links resilience science with long-term outcomes. By applying resilience approaches, management systems foster human as well as ecosystem capacity to deal with climate driven changes. Better health of the ecosystem, preservation of its diversity and resources, securing water supplies, and reduced risk are some of the sustainable outcomes of adaptive governance systems. Management decisions based on anticipation and proactive planning as opposed to reacting to crisis, can improve the ecological condition, enhance recovery, secure fresh water resources and help achieve environmental sustainability. Climate informed adaptation, ensures that the policies and institutions adopted will not create future vulnerabilities or jeopardise the resilience of ecosystems [25]. In the realm of social institutions adaptive governance promote collaborative relationships between all stakeholders, which would improve understanding among themselves and their actions. Sustained and long-term monitoring of an ecosystem will also enhance its sustainable outcomes by facilitating the adjustment of strategies over time based on the feedback acquired. Therefore, good governance with good adaptive capacity can ensure healthy ecosystems that can offer crucial services under continuing climate change, which matches closely with global efforts toward sustainability, including conserving diversity and ensuring the security of fresh water [9-26].

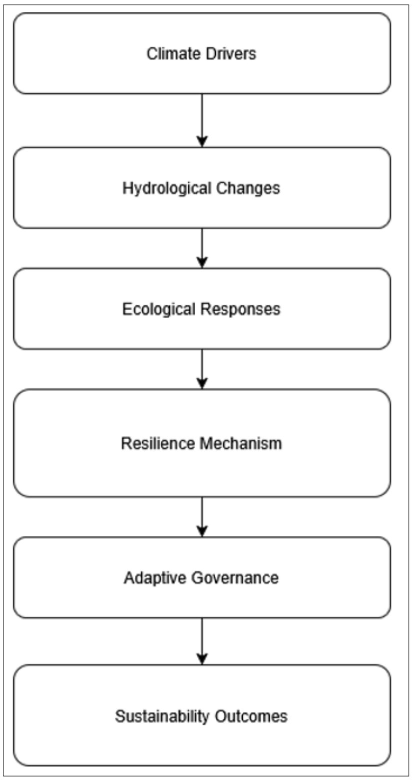

Figure 2: Integrated Framework for Freshwater Ecosystem Resilience

As Fig 2 shows, there is climate drivers on the top influencing hydrological changes; hydrological changes will influence the responses of the ecosystem which means losing diversity of species, changing habitat structures and altering functions; there are some resilience mechanisms that could buffer the changes, including diversity of species, ecological connections, ecological memory, and adaptive capacity, and adaptive governance intervention actions such as restoration, watershed management, monitoring which could strength the resilience mechanisms, finally there are sustainability outcomes that emerged from a resilient ecosystem which have improved ecosystem health, maintained the biodiversity, and maintained the security of water supply, and adapted to the climate change; meanwhile there is feedback loop from the sustainability outcomes to governance and ecological processes which showed the dynamic characteristics of resilience.

Research Gaps and Future Priorities

There are several major limitations on current research about resilience, including: Limited long-term ecological data, which are difficult for assessing ecological changes due to late ecosystem responses to some stimuli; freshwater ecosystems of Africa were rarely investigated, and their vulnerability to climate change; integrating of the ecosystem, hydrology, socio-economics in resilience assessment study were limited; more works have focused on the resistance of the ecosystem than resilience of regeneration and transformation; quantification of ecological resilience threshold is immature; uncertainty arising from climate projection has increased difficulty to resilience assessment; insufficient concern of indigenous knowledge and community based adaptation was a challenge for resilient strategies; coupled impacts from different stressors such as pollutants, land use, invasive species were largely unexplored; interdisciplinary approaches integrating ecological monitoring, climate modeling, governance analysis, stakeholder participation should be adopted and they is fundamental for building reliable strategy which can strengthen the resilience of freshwater ecosystems with accelerated climate change.

Conclusion

The accelerating climate change is profoundly altering freshwater ecosystem functioning through amplified hydrological disturbance regimes, and it will threaten the integrity and long-term existence of aquatic biota. Resilience allows aquatic ecosystems to absorb disturbances, reorganize and transform in response to shifting climatic conditions. Ecosystem resilience is affected by a multitude of ecosystem and governance elements such as diversity of species, connectivity of ecological networks, adaptive governance and ecosystem-based management. Hence, freshwater resilience can be strengthened by addressing multiple challenges such as uncertainties, non-linear responses, and temporal trajectories through transdisciplinary approaches.

Author Contributions

The author designed the study, read the manuscript, and approved the final paper to be submitted.

Competing Interests

No competing interest declared.

Funding

No external funding was obtained for this study.

References

1. Dahal D, Bhattarai N, Silwal A, Shrestha S, Shrestha B, et al. (2025) A Review on Climate Change Impacts on Freshwater Systems and Ecosystem Resilience Water 17: 3052.
2. Jeyachandran S (2025) Review on climate change, microbial resilience, and disease risks in global aquaculture systems. Comparative Immunology Reports 9.
3. Sarhan AA (2021) Towards a Blue Economy in Egypt: Economic Assessment of Environmental Degradation of Marine and Coastal Resources. J Environ Sci 50: 63-83.
4. El-Ghani SSA, Dosoky ANS, Sharaa DEII, Mohamed SA F (2026) Econometric Analysis of the Impact of Climate Change on the Performance of Egypt's Fish Foreign Trade. Sustainability18: 5610.
5. Liu S, Xie Z, Liu B, Wang Y, Gao J, et al. (2020) Global River water warming due to climate change and anthropogenic heat emission. Global and Planetary Change 1-193.
6. Johnson MF, Albertson LK, Algar AC, Dugdale SJ, Edwards P, et al. (2024) Rising water temperature in rivers: Ecological impacts and future resilience. WIREs Water 11: e1724.
7. Dinh DA, Tong Y, Feng L, Fleischmann A, Jennings E, et al. (2026) Emerging changes in lake temperature extremes and variability in South America. Climatic Change 179: 41.
8. Woolway RI, Kraemer BM, Lenters JD (2020) Global Lake responses to climate change. Nat Rev Earth Environ 1: 388-403.
9. IPCC (2023) Climate Change 2023: Synthesis Report. Geneva, Switzerland: Intergovernmental Panel on Climate Change.
10. Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, et al. (2021) Extreme Weather and Climate Change: Population Health and Health System Implications. Annual review of public health 42: 293-315.
11. Caretta MA, Mukherji A, Arfanuzzaman M (2022) Water. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press 551-712.
12. Goodbred SL, Sr Patiño R, Alvarez DA, Johnson D, Hannoun D, et al. (2024) Fish Health Altered by Contaminants and Low

Water Temperatures Compounded by Prolonged Regional Drought in the Lower Colorado River Basin, USA. Toxics 12: 708.
13. Amparo-Salcedo M, Pérez-Gimeno A, Navarro-Pedreño J (2025) Water Security Under Climate Change: Challenges and Solutions Across 43 Countries. Water 17: 633.
14. Dakos V, Matthews B, Hendry AP, Levine J, Loeuille N, et al. (2019) Ecosystem tipping points in an evolving world. Nature Ecology & Evolution 3: 355-362.
15. Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413: 591-596.
16. Isbell F, Cowles J, Dee LE (2023) Biodiversity increases the resistance, resilience and stability of ecosystems as environmental change intensifies. Nature 622: 136-144.
17. Fisher JC, Dallimer M, Irvine KN (2023) Human well-being responses to species' traits. Nat Sustain 6: 1219-1227.
18. Alvarez-Martinez R, Miramontes P (2026) Early Warning Signals in Ecological Time-Series. Entropy 28: 628.
19. Reid AJ, Carlson AK, Creed IF (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 94: 849-873.
20. Thorogood R, Mustonen V, Aleixo A, Aphalo PJ, Asiegbu FO, et al. (2023) Understanding and applying biological resilience, from genes to ecosystems. npj biodiversity 2: 16.
21. Folke C, Carpenter SR, Walker B, Scheffer M, Chapin T, et al. (2010) Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society 15: 20.
22. Magdy (2025) Ecological resilience and adaptive management. A guide for researchers and conservationists. https://www.ierek.com/news/ecological-resilience-and-adaptive-management/.
23. Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30: 441-473.
24. Chaffin BC, Gosnell H, Cosens BA (2016) A decade of adaptive governance scholarship: Synthesis and future directions. Ecology and Society 21: 56.
25. Brown C (2025) Climate-Informed Decision Analysis Via Decision Scaling. Uncertainty in Climate Change Research. Springer 19-29.
26. United Nations (2023) The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. UNESCO Publishing https://www.unwater.org/publications/un-world-water-development-report-2023.

Copyright: ©2026 Francis Olawale Abulude, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.