ISSN: 2978-3801

Journal of Global Warming and Climate Change

SCIENTIFIC Research and Community

Review Article

Open Access

The Relationship Between Water Quality and Keystone Species Loss in Lake Ecosystem

Sakshi Dange[1], Kumaraguru Arumugam[2] and Sai Saraswathi Vijayaragavalu[1]*

[1]School of Advanced Sciences, Vellore Institute of Technology, Tamil Nadu, India

[2]Tamil Nadu Forest Department and Biodiversity Conservation Foundation, Tamil Nadu, India

ABSTRACT

Keystone species have a significant impact on the lake's ecosystem, biodiversity management, and water quality. This review explores the complex interconnections between adverse water quality deterioration and loss of keystone species in lakes, with a focus on pollution, fragmentation and climate change. Nutrient pollution and eutrophication are the leading causes of poor water quality and have been a major cause of the decline of keystone species, for example, fish, amphibians and invertebrates that are important in controlling the trophic cascade and organising structural complexity of the habitat. The extinction of these species triggers a series of occurrences that worsen water quality, establishing a feedback loop that worsens problems with ecosystem health and solutions. The study also includes several keystone case studies on species restoration, water quality research, integrated management, and invasive species control measures that demonstrate habitat and community involvement. Long-term monitoring is required to assess the efficacy of climate-resilient techniques, restoration, and species interactions in responding to pressures. Given that climate change may exacerbate such pressures, it is critical to have management approaches and preventive measures in place, such as maintaining climate refugia and improving connectivity within aquatic ecosystems, as well as restoration and enhancement of keystone species in lakes. The findings underline the necessity for a collaborative, multi-stakeholder approach to managing freshwater ecosystems to retain keystone species and maintain ecological equilibrium in lakes.

***Corresponding author**

Sai Saraswathi Vijayaragavalu, School of Advanced Sciences, Vellore Institute of Technology, Tamil Nadu, India.

Received: September 23, 2025; **Accepted:** September 27, 2025; **Published:** October 05, 2025

Keywords: Biodiversity Loss, Climate-Resilient Strategies, Eutrophication, Keystone Species, Lake Ecosystems

Abbreviation

BMPs – Best Management Practices
EBM – Ecosystem-Based Management
GLWQA – Great Lakes Water Quality Agreement
IPCC – Intergovernmental Panel on Climate Change
NBS – Nature-Based Solutions
PCBs – Polychlorinated Biphenyls
PAHs – Polycyclic Aromatic Hydrocarbons
SDGs – Sustainable Development Goals
WHO – World Health Organization

Lakes are important ecosystems that are biodiversity hotspots and deliver essential ecosystem services, ranging from water supply to food production, recreational activities, and cultural values. Lakes cover a very small proportion of the Earth's surface but contribute disproportionately to terrestrial biodiversity, supporting a diversity of species, many of which are endemic and highly specialised to these habitats. In such ecosystems, some species, referred to as keystone species, have a disproportionate influence in upholding the structural stability and ecosystem processes of their ecosystems. Keystone species are essential components of ecosystems; their presence or absence [1]. Significantly influences community structure, affecting both biodiversity and ecosystem stability. For instance, in most lakes, apex predators like some fish species control the prey species, which in turn keeps the food web and other ecosystem processes in balance [2]. Freshwater ecosystems are, however, among the most endangered in the world, with lakes suffering unprecedented levels of degradation resulting from the synergy of human-induced pressures. These encompass pollution, land use changes, habitat fragmentation, invasions by non-native species, and, more recently, the effects of climate change [3]. Perhaps the greatest threat to lake ecosystems is the deterioration of water quality, which is caused primarily by nutrient pollution and results in eutrophication and toxic algal blooms [4]. These water quality changes have direct and indirect impacts on keystone species, which are often extremely sensitive to changes in their environmental conditions. When water quality decreases, these species experience habitat loss, changes in food webs, and heightened competition from more tolerant non-native invaders, eventually resulting in population decline or extirpation [5]. Water quality decline and loss of keystone species are interrelated in a complicated and multifaceted sense. In one sense, poor water quality, particularly from excessive amounts of nutrients like phosphorus and nitrogen, leads to eutrophication that depletes oxygen and renders the environment unliveable for most keystone species. For example, in Lake Erie, nutrient pollution led to severe hypoxia, causing the collapse of key fish populations such as walleye and yellow perch, which are crucial for maintaining the lake's food web structure [6]. On the other hand, the destruction of keystone species can exacerbate water quality issues, creating a feedback loop that expands ecosystem degradation. For instance, when herbivorous invertebrates or fish that control algae populations lose their attachment, algal blooms intensify and become more recurrent, worsening water quality and leading to additional species loss [7]. Keystone species extinction has major implications for lake systems. These species often support a range of ecological processes, such as nutrient cycling, primary production, and habitat structure, that are important for the overall health of the system. For instance, when a keystone predator is lost, this can lead to trophic cascades in which top-down control is lost, and this results in population explosions of lower trophic level populations, which disrupts the whole system's balance [8]. In aquatic ecosystems, these kinds of cascading effects are commonly observed where predator fishes are lost, thus leading to increased numbers of herbivorous fishes, overgrazing of aquatic vegetation, and subsequent loss of water transparency and environmental quality [9]. Due to the key role played by keystone species in maintaining lake ecosystem integrity, efforts towards restoring and conserving keystone species are important. Successful keystone species recovery typically involves some level of habitat restoration, pollution reduction, and specifically targeted management of the species. Restoration of wetlands by reconstructing them and the creation of riparian buffers, for example, can improve water quality by filtering out runoff and providing necessary habitat for keystone species. Further, adaptive management interventions such as the modification of fisheries regulations, control of invasive species, and restoration of natural hydrologic regimes are crucial in creating conditions favourable to the persistence of keystone species even under a change in environmental conditions [10]. Yet another of the fundamental issues for the management of lake ecosystems is the interaction of local stressors such as nutrient runoff and habitat destruction with global change, particularly climate change. Climate change acts as a "threat multiplier" in that it exacerbates existing stressors and introduces new ones, such as altered patterns of precipitation, increased water temperatures, and heightened frequency of extreme weather events [11]. These changes have been found to disrupt thermal stratification in lakes, change the timing and extent of ice cover, and alter species distribution, all of which have wide-ranging implications for keystone species that are highly adapted to highly specific environmental conditions. For example, warming in cold-water lakes can reduce habitat quality for lake trout and lead to population loss and a ripple effect across the ecosystem [12]. The emergent complexity of water quality-keystone species-broad process interactions confirms the need for holistic, multi-disciplinary approaches to lake management. Effective conservation efforts need to take into account the interconnectedness of the ecological processes, the diversity of the stakeholders affected, and the socio-economic conditions influencing land and water use. Additionally, adaptive management structures that place importance on monitoring, adaptability, and community participation are instrumental in the management of uncertainties and dynamics related to managing lake ecosystems in altered environments [13]. This review article attempts to analyse the intricate relationship between water quality and keystone species loss in lake ecosystems, utilising case studies from around the world to illustrate the impacts of deterioration and opportunities for restoration. With the review of effective restoration and identifying areas of growing research need, this article seeks to provide illumination into how lake ecosystems can be better managed in an attempt to preserve their biodiversity and ecological stability in the face of ongoing environmental stresses. The merit of pursuing scientifically obtained information, policy structure, and locally based practice for conservation will be emphasised as key components in effective management and recovery of lake keystone species.

Methods for Keystone Species Recovery in Lakes

Restoration of lake keystone species requires an integrated approach involving restoration of habitat and mitigation of underlying causes for water quality decline. Habitat restoration is perhaps the most important technique, which involves the reintroduction of native aquatic vegetation and the establishment of structural elements like fish refuges or artificial reefs. These alterations provide keystone species with required breeding and refuge habitats [5]. Besides habitat restoration, water quality management is also critical, e.g., reducing nutrient loading via agricultural best management practices and restricting algal blooms via aeration, bio-manipulation, or selective chemical control4. Keystone species reintroduction and restocking is also important method. Effective restocking schemes and assistance breeding programs can re-stock fish, amphibian, and invertebrate keystone species important to keeping ecosystems in balance [14]. Eradication of invasive species is also needed, as such species will compete with or prey upon native keystone species and hinder efforts at recovery. Targeted removal strategies, including mechanical harvesting and biological control, are employed to mitigate their impact [15]. Equally important is engaging local communities and stakeholders in restoration efforts. Public education, policy-making, and collaborative conservation measures are required for ultimate success [13]. Adaptive management and continuous monitoring finally ensure that restoration work is successful and can be revised as necessary with new data [9]. This comprehensive strategy for species recovery not only helps to re-establish keystone species but also retains healthier, more resilient lake ecosystems overall.

Adaptation Strategies to Mitigate the Effects of Climate Change on Keystone Species

Adaptation strategies for reducing the effects of climate change on lake keystone species require proactive management and actions aimed at resilience enhancement. One key strategy is the conservation and enhancement of climate refugia areas in lakes that are relatively stable under climate change. Conservation of colder, deeper lake zones can provide critical refuges for cold-adapted species that are extremely vulnerable to warming [16]. Watershed management is also a vital strategy with emphasis on sustainable land use that reduces nutrient runoff and erosion, thereby preventing negative climate impacts such as enhanced algal blooms [17]. Techniques like the establishment of riparian buffer strips, wetland rehabilitation to act as natural filters, and the application of precision agriculture methods limiting excessive fertiliser application are critical [4]. Assisted migration and translocation are increasingly popular, with the movement of climate-endangered species to more suitable environments within or beyond their current range. This has been considered for fish species that are at risk of survival within their natural habitats due to the rise in temperatures [18]. Additionally, aquatic habitat reunification is necessary. Dams and culverts are eliminated as barriers to allow species to move to more favourable locations in response to changing conditions and therefore enhance their chances of survival. Monitoring and adaptive management are also key, as they enable continuous assessment of ecosystem health, species numbers, and water quality. This can enable managers to make immediate changes to practices, such as altering fishing equipment requirements or adjusting water flow regimes in controlled lakes to maximise support for keystone species in a changed scenario [9]. Education and community engagement are also essential. Engaging local communities in conservation and climate awareness increases support for adaptive interventions so that interventions are more effective and sustainable in the long run [13]. The strategies also emphasise the need for adaptable, visionary interventions that enhance ecosystem resilience and react to both current and future climate impacts on keystone species in lakes.

Holistic Approaches to Protect Keystone Species and Improve Lake Water Quality

Other measures of mitigation to preserve keystone species and improve lake water quality involve a set of integrated solutions addressing both the environmental and human sides. Ecosystem-Based Management (EBM) is a multi-faceted method considering the overall ecosystem, including human undertakings, rather than having a single-issue emphasis. EBM places high priority on long-term water and land management practices such as watershed land management to reduce runoff and pollution that, in turn, promote lake health and keystone species [19]. Adaptive water management is another leading methodology, which involves water level control and seasonal regimes of flow in lakes and reservoirs to mimic natural hydrology and thus preserve necessary habitat for breeding and migration [15]. Increasing genetic diversity in keystone species populations, by processes like careful breeding and cross-breeding, can increase the resilience of species to environmental change and enable them to cope better with future challenges [20]. Pest and invasive species management, by incorporating biological, mechanical, and chemical controls, is vital to avoid invasive species from spreading and endangering native keystone species. Early detection and rapid response mechanisms are crucial in addressing these threats before they cause widespread destruction [21]. Improving protected areas and buffer zones, especially in riparian corridors and wetlands, helps in filtering out pollutants, stabilising shores, and maintaining habitat connectivity, thereby conserving key ecological functions [22]. Community-led conservation programmes, including habitat restoration, citizen science, and stewardship actions, also ensure that the conservation behaviour is acceptable and well-supported culturally [13]. Policy and governance reforms also need to consolidate environmental legislation, enforce sustainable land-use actions, and bring an end to excessive water resource appropriation, with incentives like subsidies and penalties for compliance [23]. Green infrastructure opportunities such as the construction of wetlands and restoration of floodplains can facilitate carbon sequestration, enhance water quality, and provide resilient habitats for keystone species [24]. Public awareness and education campaigns further complement these measures by instilling the link between water quality, ecosystem health, and species conservation, which promotes behavioural change, minimising pollution [25]. Finally, long-term keystone species survival is ensured through sustainable fisheries management measures such as establishing catch limits, seasonally imposing limits, and breeding protection zones [26].

Key Pollutants Impacting Lakes and Keystone Species

These key pollutants that affect lakes are nutrients such as phosphorus and nitrogen, which mainly enter via agricultural runoff, wastewater, and urban stormwater. High levels of nutrients cause eutrophication, resulting in toxic algal blooms that deplete oxygen, shade out sunlight, and produce toxins dangerous to aquatic organisms and humans alike. This degradation destabilises lake ecosystems and induces loss of keystone species [27]. Sediments, typically from erosion due to deforestation, agriculture, and construction, are also big threats. High sediment loads lower water clarity, bury essential habitats, and transport pollutants like phosphorus, heavy metals, and pesticides into lakes [28,29]. Industrial waste effluents, mining activities, and atmospheric deposition discharge heavy metals such as mercury, lead, and cadmium to the environment, which bioaccumulate in the food web with severe toxic risks to aquatic organisms and keystone species. Mercury, for example, is transformed into highly toxic methylmercury, which is retained in fish and is harmful to wildlife and human health [30]. Herbicides and pesticides from crop runoff introduce toxic chemicals that kill non-target species, destroy biodiversity, and are among the causes of the declines of keystone organisms like amphibians. Organic contaminants like PCBs and PAHs, which enter through industrial processes and urban runoff, are resistant to degradation and continue to build up in the food web with long-term impacts on lake ecosystems [31]. Emerging contaminants include pharmaceuticals and personal care products, which enter lakes through wastewater and interfere with the endocrine systems of aquatic organisms, inducing reproductive and behavioural changes in marine organisms [32]. Finally, increasingly large amounts of microplastics from synthetic apparel, weathered plastics, and personal care products enter the lakes. These small particles are ingested by aquatic animals, resulting in physical blockages and toxicities, destabilising food webs and threatening keystone species [33]. These kinds of introduced pollutants directly or indirectly lead to all sorts of ecological problems, including water quality degradation and loss of species that play vital roles in sustainable lake ecosystems.

Successful Mitigation Techniques and Challenges Faced in the Conservation of Keystone Species and the Improvement in the Water Quality of Lakes

These case studies showcase the diversity and complexity of the methods applied in restoring and maintaining lake ecosystems. Lake Erie in North America represents a classic example of integrated ecosystem management. Previously plagued by severe eutrophication issues in the 1960s and 1970s due to nutrient runoff, Lake Erie reacted dramatically with improved phosphorus regulation, improved agricultural techniques, and habitat restoration under the Great Lakes Water Quality Agreement (GLWQA). The rejuvenation of keystone species like walleye and better water quality was achieved by this multi-stakeholder, collaborative initiative [34]. Lake Victoria in East Africa suffered ecological meltdown due to the alien Nile perch, resulting in the near extermination of native cichlid species, which were key to the ecological balance of the lake. Mitigation through biological controls and community fisheries management has stabilised indigenous fish stock and improved ecosystem health despite persistent challenges [35]. Scotland's Loch Leven utilised its adaptive management system in conjunction with specific farming methodology, wetland restoration, and community engagement to successfully constrain phosphorus inputs and restore water quality. The recovery of keystone species like brown trout demonstrates how coordinated action by local stakeholders and scientific institutions can lead to long-term ecosystem recovery [36]. Lake Baikal in Russia, a World Heritage Site of UNESCO, remains at risk from pollution, climate change, and industrialisation. Since work focuses on closer pollution control and ecotourism, management concerns and biased enforcement indicate the difficulty of balancing economic growth with nature conservation [37]. Florida's Okeechobee Lake, a critical part of South Florida's water supply network, has been plagued by nutrient pollution from agricultural runoff that has resulted in harmful algal blooms and habitat loss. Restoration activities, including best management practices (BMPs) and wetland restoration, have improved water quality and keystone species habitat, although ongoing conflict between agricultural uses and ecosystem health remains a significant challenge [38]. Together, these case studies demonstrate the need for tailored, integrated strategies incorporating scientific inquiry, stakeholder engagement, and adaptive management methods for addressing the unique challenges of different lake ecosystems.

Effect on Biodiversity

The impact of these new trends in restoration on biodiversity is huge and largely positive. Nature-Based Solutions (NBS) focused on restoring ecosystems like wetlands, riparian ecosystems, and forests are pivotal in enhancing habitat complexity, which benefits species diversity. Through the restoration of natural processes such as hydrological flows and nutrient cycling, such efforts create areas where indigenous species can thrive, thus promoting biodiversity recovery [39]. Digital monitoring and AI tools also assist by making it possible to better record changes in biodiversity through time, leading to better-informed management decisions that benefit key habitats and keystone species. Community-led restoration initiatives further augment biodiversity outcomes by incorporating local and indigenous knowledge that inherently emphasises upholding diverse species as well as traditional ecosystems. This local approach ensures that restoration efforts are ecologically suited and culturally sensitive, leading to the conservation of both common and rare species [40]. Restoring ecosystems to make them climate resilient, i.e., coastal wetlands and woodlands, also creates habitats that consist of a wide range of species, thus enhancing overall biodiversity. Restoration of such locations not only acts as a refuge for species but also contributes significant ecological services like pollination, seed dispersal, and pest control, crucial to maintaining healthy ecosystems [41]. Watershed management integrated across the entire catchment leads to more rational and large-scale restoration efforts that exclude habitat fragmentation, a major risk to biodiversity. Through holistic management of pollution, land use, and hydrological modification, these methods enhance connectivity of habitats, which is crucial for both species' movement and genetic diversity [42]. Combined, these restoration trends create more long-lasting ecosystems capable of maintaining a diverse range of species, which in turn creates healthier and more resilient environments.

Directions for Future Research in Lake Ecosystems

Upcoming research in lake ecosystems must address some critical gaps to better inform our understanding and management of water quality and keystone species. Among these areas is an understanding of species-specific responses to climate change, particularly for less-well-studied invertebrates and plants. While many species have good coverage, what is needed is a more integrated view over a broader set of species to predict ecosystem-scale impacts as climate regimes shift [43]. More long-term monitoring and data for water quality monitoring and monitoring of species populations over time are badly needed. This information would help differentiate between short-term fluctuation and long-term trends, giving a clearer picture of how pollution, habitat loss, and climate change interact over time [44]. Climate-resilient restoration techniques are also something that should be researched, with an eye towards which techniques, like habitat restoration, species reintroduction, or adaptive water management, will prove effective under different climatic conditions [41]. Thresholds and tipping points within lake ecosystems are also something that needs to be identified. Awareness of when a decline or loss of keystone species becomes irreversible can prevent ecosystem collapses [45]. Furthermore, the interaction of climate change with other pressures like invasive species, pollution, and fragmentation needs to be examined because these concurrent pressures induce enhanced losses in keystone species [46]. Synoptic management approaches that can rectify compounded effects need to be explored through research. The social and economic dimensions of adaptation must also be taken into account. Interdisciplinary work on impediments to community engagement, financing problems, and the economic implications of species loss can guide more effective and just conservation action [47]. Last but not least, studies on the genetic and evolutionary adaptation capacity of keystone species represent a promising emerging field, examining whether species with short generation times can adapt quickly enough to keep pace with changing conditions [48]. This may include examining assisted evolution techniques for enhancing species resilience. Filling these gaps in research is important for developing more adaptive and sustainable lake ecosystem management plans within the context of ongoing environmental change. Tables 1 and 2 collectively illustrate how restoration strategies are implemented and how pollutant-driven ecological stressors affect keystone species, thereby underlining the interconnected challenges of water quality management.

Table 1: Comparing the Success rates of Various Restoration Procedures (for example, returning Native Species and Restoring Wetland Habitats)

Restoration Technique	Effectiveness	Cost	Scalability	Case Study Example
Wetland Restoration	High	Medium	High	Lake Erie, USA
Reintroducing Native Species	Moderate	High	Low	Loch Leven, Scotland
Nutrient Load Reduction	High	High	Moderate	Lake Victoria, Africa

Table 2: Shows Key Pollutants (such as Nitrogen, Phosphate, and Heavy Metals) and their Particular Impacts on certain Keystone Species (such as Fish and Amphibians)

Pollutant	Source	Impact on Water Quality	Keystone Species Affected
Nitrogen	Agricultural runoff	Eutrophication, Hypoxia	Fish (e.g., trout, walleye)
Mercury	Industrial discharge	Bioaccumulation, Toxicity	Birds, Predatory fish
Phosphorus	Fertilizer runoff	Harmful Algal Blooms	Amphibians, Aquatic invertebrates

Policy Implementation Challenges

Policy enforcement to protect keystone species and improve lake water quality is hampered by several challenges, primarily coordination among stakeholders, funding, enforcement, and a lack of data. Successful policy enforcement entails intermixing among different stakeholders like government agencies, local people, industries, and environmental organisations. However, competing interests can become barriers in the form of agricultural and industrial interests opposing limits on fertiliser use or enhanced wastewater treatment needs, both of which are important for preventing nutrient runoff and improving water quality [49]. Another challenge is getting a sufficient budget since conservation and restoration activities are long-term financial investments. Governments, especially in areas that lack resources, may struggle to collect the resources required for enforcement, monitoring, and community outreach programmes, and hence implementation gaps arise [50]. Even where policies are in place, there is uneven enforcement due to understaffing, limited resources, or weak political will. To illustrate, ineffective implementation allows such illegal activities as uncontrolled fishing and pollution to persist, undermining conservation efforts [51]. Bureaucratic inefficiencies and corruption fuel the non-compliance. Additionally, gaps in data and scientific expertise can limit the effectiveness of policies. Reliable, long-term water quality information, species abundance, and health of the ecosystem are vital for wise decision-making and adaptive management but are not possible for most areas because there is limited availability of resources to gather such data [52]. These concerns highlight the need for integrated approaches that combine scientific research, public involvement, and strong governance for enabling efficient policy practice in lake systems.

The pollutants affecting the lakes are directly and strongly associated with keystone species loss, which is responsible for maintaining the steadiness and health of ecosystems. High levels of nutrients such as nitrogen and phosphorus lead to eutrophication and thus, produce hypoxic (low-oxygen) areas from harmful algal blooms. This decimates food webs and reduces oxygen levels, impacting keystone species such as large predatory fish and invertebrates that rely on clear, well-oxygenated waters for reproduction and foraging [27]. As an example, algal blooms may result in fish kills, reducing prey populations of species such as walleye and bass that play a key role in maintaining prey population levels and ecological balance. Sediment pollution caused by erosion targets keystone species by smothering their habitats, like spawning grounds, and clogging the gills of aquatic life. Species like freshwater mussels that have a keystone function of filtering water to achieve clarity suffer when sediments increase, with associated water quality reduction and effects on species relying on clear waters for existence [28]. Heavy metals like mercury pose a great danger to apex predators like fish and birds, with a keystone function of keeping aquatic food webs in check. Mercury bioaccumulates and is enriched in higher trophic levels, leading to toxic impacts that can lead to the inhibition of reproduction and population declines [30]. For instance, predator fish declines can cause prey species imbalance, leading to cascades throughout the ecosystem. Pesticides and organic pollutants also affect keystone species by causing reproductive failure, behavioural changes, and even mortality. Amphibians, as keystone species because they regulate insect populations and are sensitive indicators of ecosystem health, are particularly vulnerable to pesticide contamination. Amphibian population decline can lead to increased pest species and further destabilise the ecological balance [53]. Emerging pollutants like pharmaceuticals and microplastics have subtle yet extensive impacts on keystone species by compromising hormonal processes and causing physical damage. Microplastics ingested by keystone species such as filter-feeding fish and invertebrates are found accumulating in gut systems, hindering feeding efficiency and energy storage and ultimately affecting their ecological function [33].

Examples of Adaptive Management

Adaptive management is a dynamic system that enables environmental plans to change depending on ongoing monitoring and real-time data and is particularly well-suited to deal with lake systems and keystone species. Adaptive management has been applied along the Colorado River to control water flow, replicating natural flood cycles to reconstruct riparian ecosystems and preserve native species. This strategy provides the mechanism for change in water release schedules as an ecological adjustment, reconciling human water uses with resilient ecosystems [15]. Adaptive measures in the Florida Everglades have also been practised in the restoration of the natural flow of water and the enhancement of keystone species conditions, such as the American alligator. By monitoring water levels and the health state of species continuously, water delivery systems are adjusted to restore habitats [54]. Adaptive management is used in the Great Lakes to manage invasive species like zebra mussels and sea lampreys. Strategies are formulated upon the success of control methods such as chemical treatments and biological barriers, which protect indigenous keystone species such as lake trout [55]. Adaptive management in the Columbia River Basin in the Pacific Northwest targets salmon habitat restoration through dam operation modification using real-time data on salmon migration patterns. Phosphorus input-reducing modifications, including adaptive measures, are part of Lake Erie's nutrient management plan in response to the threat from harmful algal blooms that have damaged keystone species such as walleye. Water release and temperature control modifications will assist in preserving keystone fish stocks, important species within the ecosystem and indigenous cultures [56]. Wetland restoration efforts, best management practices, and changes to agricultural practices are guided by ongoing data collection, and the process gets more efficient over time [57]. These examples show how the recursive nature of adaptive management makes conservation efforts more resilient and flexible, enabling the adaptation of techniques to improve the health of lake ecosystems and the support of keystone species.

Restoration Success Stories

There are several restoration success stories in which adaptive management and focused interventions have resulted in remarkable recovery of keystone species and enhancements of lake ecosystems. A key example is the recovery of the Bald Eagle in the Great Lakes. Following years of population decline resulting from DDT contamination, which had a subsequent eggshell thinning and reproductive failure, concerted conservation efforts like habitat protection and pollution reduction were enforced. Thus, Bald Eagle populations have bounced back strongly, illustrating how recovery of a single species can turn around declines and enhance the general health of ecosystems [58]. Another such success is the restoration of Lake Erie from a "dead lake" in the 1960s as a result of over-eutrophication caused by phosphorus pollution from agricultural runoff and sewage. By international agreements like the Great Lakes Water Quality Agreement (GLWQA) between Canada and the U.S., phosphorus inputs were reduced significantly. It brought about impressive improvements in water quality, the recovery of keystone species like the walleye, and the rehabilitation of recreational and commercial fisheries [59]. Despite ongoing issues, Lake Erie's recovery shows the power of concerted policy, science, and community effort in restoring depleted ecosystems. The Danube River Basin in Europe is similarly an excellent example of a restoration success story. Fish passes and river re-meandering projects have rebuilt migratory corridors for fish such as the sturgeon, a keystone species of special significance to the ecological health of the river. By reconnecting habitats and restoring natural flow regimes, these projects have made it possible to partially restore sturgeon populations and enhance basin-level biodiversity [60]. Finally, restoration of the Mississippi River Delta wetlands has generated considerable ecological dividends. After widespread wetland destruction as a result of levee building and other human activity, large-scale restoration through sediment diversion and marsh recovery has recovered important habitat. These restored wetlands deliver significant ecosystem benefits such as purifying waters, storm buffering, and habitat for keystone species such as the American alligator and the migratory birds that are also keystone species and engage in upkeep of ecological balance [61]. Such illustrations showcase that synergy-based restoration practices, with scientific expertise, adaptive management, and robust governance, result in enhanced results for keystone species and ecosystem health overall.

Keystone Species Role

Keystone species play a pivotal role in maintaining the structure and stability of ecosystems by regulating population processes and ecological processes. For example, in aquatic environments of freshwater lakes, lake trout is a top predator species that maintains densities of smaller fish and keeps a food web in equilibrium [12]. Their decline can initiate a trophic cascade where the absence of predatory regulation results in overpopulation of smaller fish and invertebrates that destabilise aquatic plants and nutrient pathways. In marine ecosystems, the sea otter is a typical keystone species, preying on sea urchins that feed on kelp forests [7]. If there were no otters, the urchin populations would get out of hand and destroy kelp forests, which are critical habitats for numerous marine species. On land, the African elephant is a keystone species in itself by modifying the habitat with its diet, producing open spaces for other plants to develop. By creating destruction through the uprooting of trees and trampling over plants, elephants play a role in the sustenance of the savannah ecosystem and promote biodiversity [62]. Their loss can lead to massive ecological imbalance, thus demonstrating their role in sustaining ecosystem stability.

Effect of Water Quality on Keystone Species: The Role of Nitrogen, Phosphorus, and Heavy Metals in Ecosystem Degradation

Degradation of water quality through some pollutants, such as nitrogen and phosphorus, is one of the major drivers of keystone species extinction in aquatic communities. The pollutants, primarily from agricultural runoff, wastewater discharges, and industrial processes, induce eutrophication, an area where surplus nutrients result in algal and phytoplankton overgrowth. This rapid algae growth lowers the levels of oxygen in the water, forming hypoxic (low-oxygen) conditions that are usually fatal to the majority of aquatic keystone species. For example, excess nitrogen and phosphorus in lakes and rivers can lead to the population decline of fish such as walleye and trout, which play a significant role in maintaining the balance of aquatic food webs by controlling populations of invertebrates and small fish [27]. Phosphorus, a key eutrophication driver, leads to harmful algal blooms that shade aquatic flora by blocking light, restricting aquatic plant growth and reducing habitat quality. Once the algae die and are decomposed, they use huge quantities of oxygen, adding further stress to keystone species. In Lake Erie, for instance, phosphorus nutrient contamination resulted in widespread hypoxia, contributing to the decline of predator fish that are critical to prey species regulation and ecosystem integrity [6]. Heavy metals like mercury and lead, which have a tendency to find their way into water bodies through industrial effluents, get bioaccumulated and biomagnified in the top predators' body tissue, like fish and amphibians. These toxins lead to reproductive damage, deformation, and even extinction of populations, further compromising aquatic ecosystems. Removal of these keystone species destroys nutrient cycling, energy transport, and the structure of habitats, leading to overall degradation of the ecosystem.

Conclusion

The intricate interrelationship between water quality and the preservation of keystone species in lake ecosystems highlights the need for holistic management approaches that address environmental as well as socio-economic determinants. The loss of keystone species, usually caused by pollution, global warming, and habitat loss, has ripple effects that can topple the entire ecosystem. Case studies affirm that restoring them effectively must involve adaptive management, public involvement, and long-term monitoring, emphasising the importance of proactive, climate-resilient measures. Climate refugia conservation, connectivity of landscapes, and sustainable land use are essential interventions in preventing future challenges. Sealing policy loopholes and the facilitation of community-based action are essential to building robust ecosystems that can withstand shifting environmental stress. Targeted research into species-specific responses and the synergistic effect of combined stressors will be crucial in the future for developing targeted interventions. This research highlights the imperative to adopt holistic practices that strive to reintroduce keystone species while ensuring the sustainability and resilience of freshwater ecosystems in the face of current and future threats.

References

1. Paine RT (1969) A note on trophic complexity and community stability. The American Naturalist 103: 91-93.
2. Carpenter SR, Kitchell JF (1996) The trophic cascade in lakes. Cambridge University Press. https://www.cambridge.org/core/books/trophic-cascade-in-lakes/7E7D2FD4FA33892B4F8407C02DDE9A85.
3. Schindler DW (2006) Recent advances in the understanding and management of eutrophication. Limnology and oceanography 51: 356-363.
4. Carpenter SR, Bennett EM (2011) Reconsideration of the planetary boundary for phosphorus. Environmental Research Letters 6: 014009.
5. Aldous A, Fitzsimons J, Richter B, Bach L (2011) Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. Marine and freshwater research 62: 223-231.
6. Makarewicz JC, Bertram P (1991) Evidence for the restoration of the Lake Erie ecosystem. Bioscience 41: 216-223.
7. Estes JA, Terborgh J, Brashares JS, Power ME, Berger J, et al. (2011) Trophic downgrading of planet Earth. science 333: 301-306.
8. Zedler JB (2000) Progress in wetland restoration ecology. Trends in ecology & evolution 15: 402-407.
9. Holling CS, Walters C (1978) Adaptive environmental assessment and management. https://pure.iiasa.ac.at/id/eprint/823/1/XB-78-103.pdf.
10. Mbow HOP, Reisinger A, Canadell J, O'Brien P (2017) Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2). IPCC. https://archive.ipcc.ch/report/srccl/pdf/sr2_background_report_final.pdf.
11. Magnuson JJ, Robertson DM, Benson BJ, Wynne RH, Livingstone DM, et al. (2020) Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289: 1743-1746.
12. Gunn J, Steedman RJ, Ryder R (2003) Boreal shield watersheds: lake trout ecosystems in a changing environment. https://www.taylorfrancis.com/books/edit/10.1201/9780203495087/boreal-shield-watersheds-robert-john-steedman-john-gunn-richard-ryder.
13. Pretty J, Smith D (2004) Social capital in biodiversity conservation and management. Conservation biology 18: 631-638.

14. Mantyka-Pringle CS, Martin TG, Moffatt DB, Udy J, Olley J, et al. (2016) Prioritizing management actions for the conservation of freshwater biodiversity under changing climate and land-cover. Biological Conservation 197: 80-89.
15. Poff NL, Zimmerman JK (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater biology 55: 194-205.
16. Mitchell MG, Bennett EM, Gonzalez A (2013) Linking landscape connectivity and ecosystem service provision: current knowledge and research gaps. Ecosystems 16: 894-908.
17. Schindler DW, Hecky RE (2009) Eutrophication: more nitrogen data needed. Science 324: 721-722.
18. Olden JD, Kennard MJ, Lawler JJ, Poff NL (2011) Challenges and opportunities in implementing managed relocation for conservation of freshwater species. Conservation Biology 25: 40-47.
19. Brussard PF, Reed JM, Tracy CR (1998) Ecosystem management: what is it really? Landscape and Urban Planning 40: 9-20.
20. Allendorf FW, Luikart GH, Aitken SN (2012) Conservation and the genetics of populations. John Wiley & Sons. https://www.wiley.com/en-us/+and+the+Genetics+of+Populations%2C+2nd+Edition-p-9780470671450.
21. Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, et al. (2013) Impacts of biological invasions: what's what and the way forward. Trends in ecology & evolution 28: 58-66.
22. Hansen AJ, DeFries R (2007) Ecological mechanisms linking protected areas to surrounding lands. Ecological applications 17: 974-988.
23. Young OR, King LA, Schroeder H (2008) Institutions and environmental change: principal findings, applications, and research frontiers. http://mitp-content-server.mit.edu:18180/books/content/sectbyfn?collid=books_pres_0&id=7920&fn=9780262240574_ind_0001.pdf.
24. Matthews T, Lo AY, Byrne JA (2015) Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. Landscape and urban planning 138: 155-163.
25. Jacobson SK, McDuff MD, Monroe MC (2015) Conservation education and outreach techniques. Oxford University Press. https://global.oup.com/academic/product/conservation-education-and-outreach-techniques-9780198716693?cc=in&lang=en&.
26. Pauly D, Christensen V, Dalsgaard J, Froese R, Torres Jr F (1998) Fishing down marine food webs. Science 279: 860-863.
27. Smith VH, Tilman GD, Nekola JC (1999) Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental pollution 100: 179-196.
28. Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, et al. (2005) Fine-grained sediment in river systems: environmental significance and management issues. River research and applications 21: 693-717.
29. Dange S, Arumugam K, Vijayaraghavalu SS (2024) Geochemical Insights into Heavy Metal Contamination and Health Hazards in Palar River Basin: A Pathway to Sustainable Solutions. Ecological Indicators 166: 112568.
30. Wiener JG, Krabbenhoft DP, Heinz GH, Scheuhammer AM (2002) Ecotoxicology of mercury. In Handbook of ecotoxicology: 433-488.
31. Schwarzenbach RP, Escher BI, Fenner K, Hofstetter TB, Johnson CA, et al. (2006) The challenge of micropollutants in aquatic systems. Science 313: 1072-1077.
32. Daughton CG, Ternes TA (1999) Pharmaceuticals and personal care products in the environment: agents of subtle change? Environmental health perspectives 107: 907-938.
33. Wagner M, Scherer C, Alvarez-Munoz D, Brennholt N, Bourrain,X, er al. (2014) Microplastics in freshwater ecosystems: what we know and what we need to know. Environmental Sciences Europe 26: 1-9.
34. Watson SB, Miller C, Arhonditsis G, Boyer GL, Carmichael W, et al. (2016) The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. Harmful algae 56: 44-66.
35. Kitchell JF, Schindler DE, Ogutu-Ohwayo R, Reinthal PN (1997) The Nile perch in Lake Victoria: interactions between predation and fisheries. Ecological Applications 7: 653-664.
36. May L, Spears BM (2015) Loch Leven: 40 years of scientific research: Understanding the links between pollution, climate change and ecological response. Springer. https://link.springer.com/book/10.1007/978-94-007-4333-5.
37. Timoshkin OA, Samsonov DP, Yamamuro M, Moore MV, Belykh OI, et al. (2016) Rapid ecological change in the coastal zone of Lake Baikal (East Siberia): Is the site of the world's greatest freshwater biodiversity in danger? Journal of Great Lakes Research 42: 487-497.
38. Havens KE, Gawlik DE (2005) Lake Okeechobee conceptual ecological model. Wetlands 25: 908-925.
39. Seddon N, Chausson A, Berry P, Girardin CA., Smith, A., Turner, B (2020) Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B 375: 20190120.
40. Chausson A, Turner B, Seddon D, Chabaneix N, Girardin CA, et al. (2020) Mapping the effectiveness of nature-based solutions for climate change adaptation. Global Change Biology 26: 6134-6155.
41. Hobbs RJ, Higgs ES, Hall C (2013) Novel ecosystems: intervening in the new ecological world order. John Wiley & Sons: 16-28.
42. Loucks DP, Van Beek E, Loucks DP, Van Beek E (2017) Water resources planning and management: An overview. Water resource systems planning and management: an introduction to methods, models, and applications: 1-49.
43. Cavicchioli R, Ripple WJ, Timmis KN, Azam F, Bakken LR, et al. (2019) Scientists' warning to humanity: microorganisms and climate change. Nature Reviews Microbiology 17: 569-586.
44. Donohue I, Hillebrand H, Montoya JM, Petchey OL, Pimm SL, et al. (2016) Navigating the complexity of ecological stability. Ecology letters 19: 1172-1185.
45. Groffman PM, Baron JS, Blett T, Gold AJ, Goodman I, Gunderson LH, Wiens J (2006) Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems 9: 1-13.
46. Brook BW, Sodhi NS, Bradshaw CJ (2008) Synergies among extinction drivers under global change. Trends in ecology & evolution 23: 453-460.
47. Williston B (2015) The Anthropocene project: Virtue in the age of climate change. https://www.google.co.in/books/edition/The_Anthropocene_Project/6oBcCgAAQBAJ?hl=en&gbpv=1&dq=inauthor:%22Byron+Williston%22&printsec=frontcover.
48. Hoffmann AA, Sgrò CM (2011) Climate change and evolutionary adaptation. Nature 470: 479-485.
49. Challies E, Newig J, Kochskämper E, Jager NW (2017) Governance change and governance learning in Europe: Stakeholder participation in environmental policy implementation. Policy and Society 36: 288-303.

50. Horgan FG, Kudavidanage EP (2021) Translating research into wildlife conservation actions through multi-sector collaboration in tropical Asia. Closing the Knowledge-Implementation Gap in Conservation Science: Interdisciplinary Evidence Transfer Across Sectors and Spatiotemporal Scales: 371-411.
51. Owen D (2023) The negotiable implementation of environmental law. Stan L Rev 75: 1-67.
52. Hanna DE, Tomscha SA, Ouellet Dallaire C, Bennett EM (2018) A review of riverine ecosystem service quantification: Research gaps and recommendations. Journal of Applied Ecology 55: 1299-1311.
53. Relyea RA (2005) The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities. Ecological applications 15: 618-627.
54. Gunderson LH, Holling CS, Light SS (1995) Barriers and bridges to the renewal of regional ecosystems. Columbia University Press. https://cup.columbia.edu/book/barriers-and-bridges-to-the-renewal-of-regional-ecosystems/9780231101028/.
55. Hecky RE, Smith RE, Barton DR, Guildford SJ, Taylor WD, et al. (2004) The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 61: 1285-1293.
56. Williams RN (2005) Return to the river: restoring salmon back to the Columbia River. Restoration Ecology 15: 747-748.
57. Scavia D, Bertani I, Obenour DR, Turner RE, Forrest DR, KatinA (2017) Ensemble modeling informs hypoxia management in the northern Gulf of Mexico. Proceedings of the National Academy of Sciences 114: 8823-8828.
58. Bowerman WW, Best DA, Grubb TG, Zimmerman GM, Giesy JP (1998) Trends of contaminants and effects in bald eagles of the Great Lakes basin. Environmental Monitoring and Assessment 53: 197-212
59. Dolan DM (1993) Point source loadings of phosphorus to Lake Erie: 1986–1990. Journal of Great Lakes Research 19: 212-223.
60. Sommerwerk N, Bloesch J, Paunović M, Baumgartner C, Venohr M, et al. (2010) Managing the world's most international river: the Danube River Basin. Marine and Freshwater Research 61: 736-748.
61. Day JW, Boesch DF, Clairain EJ, Kemp GP, Laska SB, et al. (2007) Restoration of the Mississippi Delta: lessons from hurricanes Katrina and Rita. science 315: 1679-1684.
62. Haynes G (2012) Elephants (and extinct relatives) as earth-movers and ecosystem engineers. Geomorphology 157: 99-107.