

Biodiversity Loss in Freshwater Ecosystems: Threats, Indicators, and Conservation Approaches

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Abstract

Freshwater ecosystems, despite comprising less than 1% of Earth's surface, harbor disproportionate biodiversity, supporting 10% of known species and facing unprecedented decline rates exceeding those in terrestrial or marine environments. This review synthesizes the global status of freshwater biodiversity loss, highlighting taxonomic vulnerabilities among fishes (26-33% threatened), decapod crustaceans (30%), odonates (16%), and molluscs (~36%), driven by habitat fragmentation, pollution, invasive species, and hydrological alterations. Quantitative analyses reveal extinction rates 100 times above background levels, with regional hotspots in North America and Europe. The paper examines genetic implications of fragmentation, functional shifts from chemical pollution, and advanced indicators like the Index of Biotic Integrity (IBI), environmental DNA (eDNA), and remote sensing for ecosystem health assessment. Conservation strategies emphasize Freshwater Protected Areas, Nature-Based Solutions (NBS), and policy frameworks such as the Kunming-Montreal Global Biodiversity Framework and Ramsar Convention. Case studies from Lake Victoria and the Mekong River illustrate synergistic threats and restoration potential. Urgent, integrated actions are essential to bend the curve of biodiversity loss and sustain ecosystem services amid intensifying anthropogenic pressures.

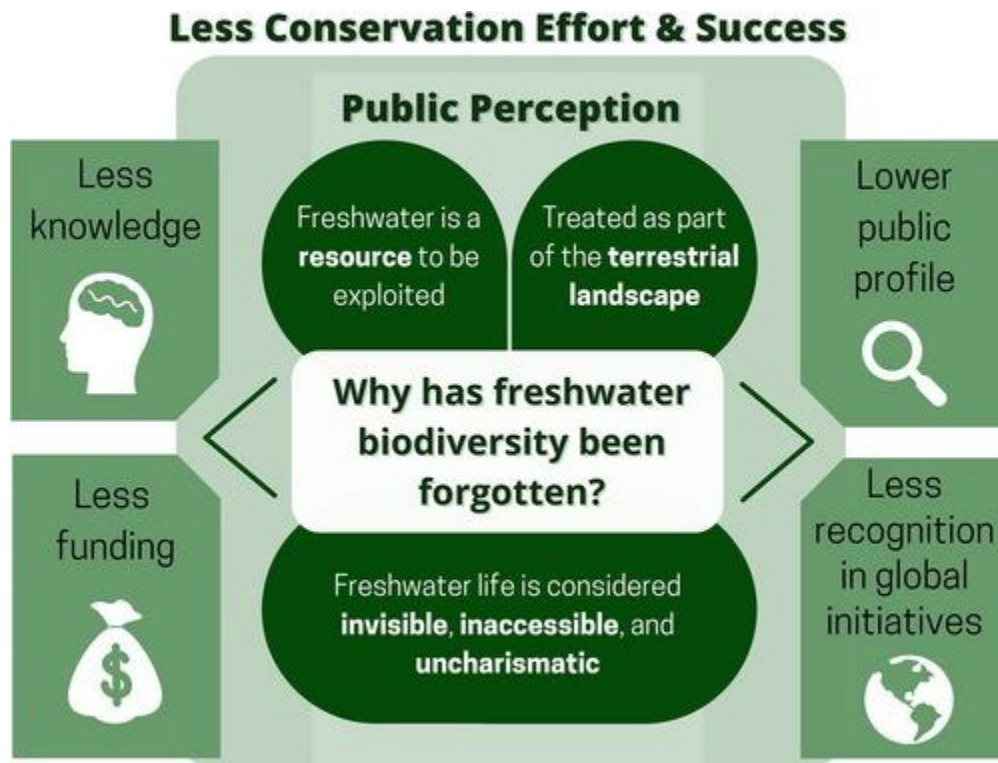
Keywords: Freshwater Biodiversity, Extinction Rates, Habitat Fragmentation, Chemical Pollution, Biotic Integrity, Environmental DNA, Conservation Planning, Nature-Based Solutions, Ramsar Convention, Mekong River

Introduction

Freshwater ecosystems occupy a unique and disproportionate position in the global biosphere, serving as critical nexus points for biological diversity, geochemical cycling, and human civilization (Spiridonov et al., 2025). While these habitats encompassing rivers, lakes, streams, wetlands, and groundwater systems collectively cover less than 1% of the Earth's total surface area and comprise only 0.01% of the world's total water volume, they support an astonishing density of life (Reid et al., 2019). Recent estimates indicate that freshwaters are home to at least 10% of all known species, including approximately one-third of all vertebrate species and nearly half of all global fish diversity (Sayer et al., 2025). This "freshwater paradox" the concentration of massive biological richness within a tiny physical footprint renders these systems exceptionally vulnerable to anthropogenic pressures. The current global status of freshwater biodiversity is defined by a crisis of unprecedented proportions, with rates of decline and extinction significantly outpacing those observed in even the most stressed terrestrial or marine environments (Dudgeon et al., 2006). The intrinsic value of freshwater biodiversity is matched by its immense socioeconomic importance. These ecosystems provide vital services including protein provision, water

purification, flood regulation, and cultural heritage (Tockner, 2021). However, as human demand for water resources intensifies, the tension between conservation and utilization has reached a breaking point. Approximately one-quarter of all freshwater fauna is currently threatened with extinction, a figure derived from intensive assessments of groups such as decapod crustaceans, fishes, and odonates (Barber et al., 2020). This crisis is exacerbated by a pervasive "information gap," where many species remain unknown to science or are categorized as Data Deficient (DD), potentially disappearing before their ecological roles are ever understood (Coates et al., 2023).

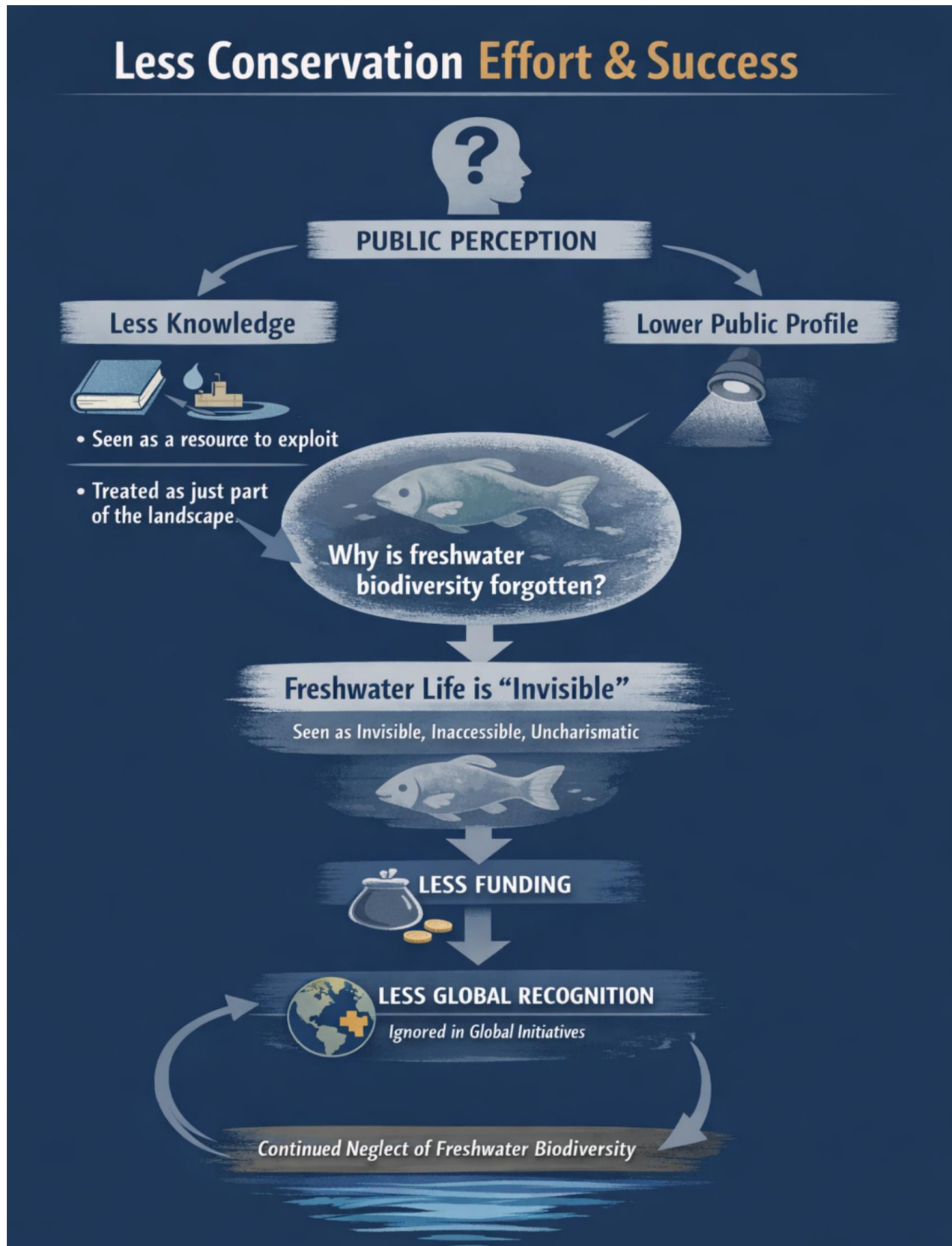
Figure 1 Public Perception and the Socio-Economic Drivers of Freshwater Biodiversity Loss



Global Status and Taxonomic Vulnerabilities

The accelerating loss of freshwater biodiversity is reflected in both population declines and species extinctions. Global monitoring suggests that freshwater vertebrate populations have declined by an average of 83% since 1970, a rate more than twice as high as that seen in terrestrial or marine systems (WWF, 2022). This decline is not uniform across taxa, as different groups exhibit varying levels of sensitivity to specific anthropogenic stressors. For instance, decapod crustaceans (shrimps and crabs) show a high threat level, with 30% of species at risk, primarily due to pollution and habitat degradation (Tickner et al., 2020). Freshwater fishes follow closely, with approximately 26% to 33% of species threatened with extinction (Sayer et al., 2025). Even groups perceived as more resilient, such as odonates (dragonflies and damselflies), face significant peril, with 16% of species threatened, largely by the direct loss of wetland habitats (Jia et al., 2018).

Figure 2. The Visibility Gap: Factors Leading to the Continued Neglect of Freshwater Species



A critical challenge in assessing the global status of these taxa is the inherent bias in conservation data. The IUCN Red List of Threatened Species, while the gold standard for assessment, is often hampered by limited information on the ecology and biogeography of most freshwater species

(Litchman et al., 2024). This results in a taxonomic bias toward large-bodied species or those with commercial significance, leaving smaller invertebrates and cryptic species under-represented. Consequently, many freshwater organisms suffer from undetected population declines while being categorized as Data Deficient rather than receiving protective status (Wymore et al., 2023).

Taxonomic Group	Estimated Percentage Threatened	Primary Threats identified	Data Deficiency (DD)
Freshwater Fishes	26% - 33%	Dams, overharvesting, change, pollution, land-use	18%
Decapod Crustaceans	30%	Pollution, habitat modification	39%
Odonates	16%	Habitat loss, land-use change	29%
Freshwater Molluscs	~36%	Pollution, habitat modification, invasive species	~36%

The biodiversity of freshwaters is also characterized by a high degree of endemism. Because many freshwater systems, such as ancient lakes or isolated river basins, act as "evolutionary islands," they host species found nowhere else on Earth (Benito et al., 2024). This lack of substitutability means that the loss of a single river reach or wetland can result in the total extinction of a species. Modern research indicates that the richness of freshwater species is likely to increase in the coming years as new species are described, particularly among invertebrates and fishes in under-sampled regions like South America and Southeast Asia (Winemiller, 2018).

Quantitative Extinction Patterns and Drivers

The modern extinction rate for freshwater fish provides a stark metric for the scale of the crisis. Between 1851 and 2016, the global extinction rate was estimated at 33.47 extinctions per million species-years (E/MSY), which is more than 100 times the natural background rate of 0.33 E/MSY (Cazzolla Gatti et al., 2016). This acceleration in species loss began in the mid-19th century but reached a critical inflection point in the mid-20th century, particularly following the 1950s and 1960s, a period coinciding with a global boom in dam construction and industrial agricultural expansion (Nelson, 2024).

Regional analysis reveals significant disparities in the magnitude of this extinction crisis. North America and Europe exhibit the highest rates of recorded extinctions, with increases over background levels reaching 684-fold and 667-fold, respectively (Davies, 2025). While Asia has a lower relative rate compared to background levels, it accounts for a high absolute number of extinctions (34 recorded), second only to North America (37) (de Jong et al., 2024).

Region	Recorded Extinctions (Fish)	Modern Extinction Rate (E/MSY)	Fold Increase over Background
North America	37	225.60	684x
Europe	20	220.26	667x
Asia	34	34.62	105x
Africa	8	13.86	42x

The primary drivers of these extinctions are categorized into several dominant and often synergistic factors. Natural System Modification (NSM), which includes dams, water extraction, and hydrological changes, is the most frequent driver, contributing to the loss of over 64% of extinct fish species (Stewardson et al., 2017). Pollution was the leading driver until the early 20th century but remains a critical threat today, particularly through the accumulation of chemical contaminants in closed basins (Ekka et al., 2020). Invasive species have become increasingly dominant as drivers since the mid-20th century, often acting in concert with habitat degradation to push native species past the threshold of recovery (Chakraborty, 2021). Notably, 84% of threatened species are affected by more than one threat, highlighting the cumulative nature of anthropogenic stress (Vardakas et al., 2025).

Habitat Fragmentation and Genetic Implications

One of the most insidious threats to freshwater biodiversity is anthropogenic habitat fragmentation. The linear and dendritic structure of river systems makes them uniquely susceptible to connectivity loss. Globally, over one million large dams and many millions of smaller in-stream barriers, such as weirs, culverts, and road crossings, have been constructed (Brauer et al., 2020). These barriers prevent the natural migration and dispersal of aquatic fauna, which is essential for maintaining population size and genetic diversity (Fuller et al., 2015).

The impact of fragmentation is particularly severe for small-bodied and non-migratory species, whose needs are often overlooked in large-scale fishway projects designed for charismatic migratory fish (Reid et al., 2019). When populations are isolated, they experience higher rates of genetic drift and inbreeding, leading to inbreeding depression and a reduced capacity to adapt to environmental changes (Aranha 2021). In the Murray-Darling Basin (MDB) of Australia, research on the Southern Pygmy Perch (*Nannoperca australis*) has demonstrated that recent fragmentation (less than 160 years) has already led to significant population isolation and loss of genetic diversity (Borges et al., 2020).

Catchment	Site	Genetic Differentiation (FST)	Effective Population Size (Ne)
Lower Lakes	ALE	0.066	198.6
Angas	MCM	0.555	76.3
Avoca	MIC	0.409	13.7
Upper Goulburn	MER	0.467	70.4
Lachlan	LRT	0.672	18.1

The values of FST (a measure of genetic differentiation) in highly fragmented sites like the Lachlan or Angas catchments indicate profound isolation. Furthermore, the significantly reduced effective population sizes (Ne) in sites like MIC (13.7) suggest that these populations are at high risk of extirpation due to stochastic demographic events (Stojanović et al., 2025). This genetic signal of isolation can often be confounded by the natural complexity of river systems, but landscape genomics has emerged as a critical tool for identifying human-induced fragmentation (Urbina-Cardona et al., 2024).

Chemical Pollution and Functional Biodiversity Loss

Freshwater ecosystems serve as the ultimate sinks for landscape-level effluents, making them susceptible to a wide array of pollutants. Traditional concerns such as nutrient loading (nitrogen and phosphorus) leading to eutrophication are now joined by "emerging contaminants" like microplastics, pharmaceuticals, and modern pesticides (Dudgeon et al., 2006). Research has shown that a combination of biocides (insecticides and fungicides) and extreme climatic events can

explain up to 90% of the functional biodiversity changes in lake ecosystems (Eastwood et al., 2022).

The loss of biodiversity in these systems often triggers a shift in ecosystem functioning. When biological communities change due to pollution, they may not return to their original state even if the water quality partially recovers (Chakraborty, 2021). This hysteresis suggests that functional roles such as nitrogen metabolism and organic matter degradation can be permanently altered. In urbanized areas, it has been observed that phytoplankton community evenness often contributes more to ecosystem functionality than direct environmental factors, indicating that biological structure is a primary mediator of health in stressed systems (Javiya et al., 2025).

Risk quotients (RQ) are increasingly used to quantify the ecological threat posed by these chemicals. For example, polycyclic aromatic hydrocarbons (PAHs) were identified as a crucial high-risk contaminant among dozens of emerging pollutants in major river systems (Reid et al., 2019).

Indicators of Freshwater Ecosystem Health

The assessment of freshwater health has evolved from simple chemical tests to sophisticated multi-metric indices that integrate biological, physical, and chemical data (Shortle et al., 2020).

Biological Indicators and the IBI

Benthic macroinvertebrates are widely recognized as the premier biological indicators for stream health (Aunins et al., 2023). These organisms, which include insect larvae, snails, and crustaceans, spend most of their lives in the water and have varying levels of tolerance to pollution. The "EPT" taxa Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) are particularly sensitive to water quality changes and are used as "canaries in a coalmine" for aquatic health (You et al., 2021).

The Index of Biotic Integrity (IBI), originally proposed by Karr, provides a framework for evaluating ecosystem health by comparing observed biological parameters against reference conditions (Karr, 1981). This can be applied to various groups, leading to the development of the Fish-IBI (F-IBI), Benthic-IBI (B-IBI), and Plankton-IBI (P-IBI) (Karr, 1981; Vollmer et al., 2018).

Indicator Type	Group Used	Sensitivity / Utility
P-IBI	Phytoplankton / Zooplankton	Rapid response to nutrient and chemical stress
B-IBI	Benthic Macroinvertebrates	Integration of localized stressors over time
F-IBI	Fish Assemblages	Reflects long-term and catchment-scale health

A key finding in multi-metric studies is that these indices often provide divergent results. For instance, studies show that F-IBI and B-IBI results can be relatively stable over time, while the P-IBI fluctuates significantly, reflecting the different temporal scales at which these organisms respond to the environment (Ramudzuli, 2019).

Physico-chemical and Habitat Indicators

While biological indicators reveal the effects of stress, physico-chemical indicators identify the causes. Parameters such as dissolved oxygen (DO), pH, electrical conductivity (EC), and nutrient concentrations (TN, TP) provide a snapshot of the chemical regime (Verma et al., 2025). Habitat indicators, including riparian buffer width, shading, and the presence of woody debris, assess the physical structural integrity of the waterway (Mishra et al., 2023). Flow indicators are equally critical, as changes to natural flow regimes often caused by dams or water abstraction are primary drivers of degradation in systems like the Murray-Darling (Arce et al., 2024).

Monitoring Technologies and Emerging Tools

The field of freshwater conservation is being transformed by new technologies that allow for non-invasive, high-resolution monitoring (Wang, 2024).

Environmental DNA (eDNA) and RNA (eRNA)

Environmental DNA (eDNA) refers to the genetic material shed by organisms into their environment through skin, waste, or reproduction. eDNA metabarcoding allows for the simultaneous identification of multiple species from a single water sample, offering a cost-effective and scalable alternative to traditional netting or trapping (DeHart et al., 2023). This is particularly useful for detecting invasive species early, as well as monitoring rare or cryptic species that are difficult to sample manually (Hauck et al., 2023).

Environmental RNA (eRNA) is an emerging complement to eDNA. While eDNA provides information on species presence, eRNA can offer insights into the active metabolic states and biological processes of organisms, allowing managers to distinguish between living populations and the historical presence of genetic material (Thakur et al., 2024).

Recent methodological advancements have focused on making these tools more accessible. Low-cost portable filtration systems, priced at approximately 350 USD, have been developed to standardize eDNA collection in diverse field environments (Mandal et al., 2026). Robotic eDNA samplers are also being deployed to collect high-frequency samples, reducing false-negative rates and providing a more complete picture of temporal biodiversity dynamics (Farrell et al., 2021).

Remote Sensing and GIS

Remote Sensing (RS) and Geographic Information Systems (GIS) provide the spatial and temporal resolution needed to monitor ecosystems at the basin scale. Technologies like hyperspectral imaging, LiDAR, and CubeSats allow for the mapping of water quality parameters, habitat connectivity, and vegetation health across vast areas (Martínez-López et al., 2021). These tools enable the identification of "hotspots" of degradation and can be used to guide the placement of protected areas or restoration projects (Singh et al., 2022)

Technology	Application	Advantage
eDNA Metabarcoding	Community-level biodiversity monitoring	Non-invasive, identifies cryptic species
LiDAR	3D habitat structural mapping	High-resolution landscape phenotyping
Satellite RS (Sentinel)	Water quality and land-use tracking	Continuous, continental-scale observation
AI / Machine Learning	Predictive modeling and species identification	Automated analysis of complex datasets

Conservation Approaches and Management Frameworks

Effective freshwater conservation requires approaches that account for the unique hydrological and ecological connectivity of these systems (Naia et al., 2021).

Figure 1 Integrated Framework for Freshwater Biodiversity Conservation and Global Governance



Freshwater Protected Areas and CARE Principles

Systematic conservation planning in freshwaters is increasingly based on the CARE principles: comprehensiveness, adequacy, representativeness, and efficiency (Linke et al., 2011). Because rivers are connected networks, traditional terrestrial protected areas often fail to protect freshwater biodiversity if they do not include upstream drainage networks and riparian zones. Freshwater Protected Areas (FPAs) must be integrated into the wider landscape to be effective, focusing on maintaining hydrological regimes and longitudinal connectivity (Tickner et al., 2020).

Nature-Based Solutions (NBS)

Nature-based solutions (NBS) involve the protection, restoration, or sustainable management of ecosystems to address societal challenges while providing biodiversity benefits (Zhang et al., 2021).

- River Restoration: Re-establishing natural physical processes like flow and sediment movement to support native biodiversity (Dwivedi et al., 2025).

- Wetland Management: Using natural or constructed wetlands to filter pollutants, mitigate floods, and provide habitat for fish and birds (Grantham et al., 2019).
- Riparian Buffer Zones (Leibowitz et al., 2018).

International Policy and the Global Biodiversity Framework

The global policy landscape for freshwater conservation is dominated by the Kunming-Montreal Global Biodiversity Framework (KM-GBF) and the Ramsar Convention (Tickner et al., 2025)

The Ramsar Convention and Institutional Drift

The Ramsar Convention (1971) was the first international agreement focused specifically on wetlands (Ramsar Convention on Wetlands, 2018). However, despite 50 years of operation, wetlands have continued to decline in area and quality 35% lost since 1970 (Spiridonov et al., 2025). Analysis suggests the convention has suffered from "institutional drift," moving away from its original focused mandate on waterfowl habitat toward a broader, less targeted "wise use" framework (Jia et al., 2018). Reasserting its original mandate while integrating modern environmental pressures, such as using wetlands as NBS for climate change, is seen as a potential path for recovery (Coates et al., 2023).

Regional Case Studies: Successes and Challenges

Lake Victoria: The Nile Perch Introduction

The introduction of the non-native Nile perch (*Lates niloticus*) into Lake Victoria in the 1950s and 60s led to one of the most catastrophic vertebrate extinction episodes in history, decimating hundreds of endemic haplochromine cichlid species (Wymore et al., 2023). This introduction fundamentally altered the lake's trophic web, moving it from a multi-species system to one dominated by a single predator (Nelson, 2024). While the Nile perch fishery created economic "winners" in the global export market, it left local communities vulnerable to malnutrition and disrupted traditional fishing livelihoods (Njiru et al., 2018). Recent signs of Nile perch overfishing have coincided with a slight re-emergence of some native species, highlighting the potential for restoration if fishing pressure and eutrophication are managed integrally (Seehausen et al., 2003).

The Mekong River: Hydropower and Fish Migrations

The Mekong River Basin is facing an unprecedented threat from hydropower development. Large dams on the mainstream and tributaries block the long-distance migrations of millions of fish, trap sediment critical for delta health, and fundamentally change river hydrology (Ziv et al., 2012). Empirical studies show that fish biodiversity declines as the cumulative number of upstream dams increases. Maintaining free-flowing sections is critical for preserving the basin's exceptional biodiversity (Reid et al., 2019). The socio-economic costs of dam development, including reduced food security for millions of rural residents, often outweigh the projected economic benefits of power production (Litchman et al., 2024).

Conclusion

In conclusion, the escalating crisis of biodiversity loss in freshwater ecosystems underscores the urgent need for transformative conservation efforts. With vertebrate populations declining by 83% since 1970 and extinction rates far surpassing natural baselines, the interplay of drivers such as dams, pollution, invasives, and climate change demands holistic, connectivity-focused strategies. Advanced monitoring tools like eDNA, remote sensing, and multi-metric indices provide critical insights for early intervention, while frameworks including CARE principles and NBS offer pathways to resilience. Policy instruments like the Ramsar Convention and KM-GBF must evolve

to address institutional gaps and integrate socioeconomic dimensions. Case studies from Lake Victoria and the Mekong highlight both the perils of mismanagement and the promise of adaptive recovery. Ultimately, safeguarding freshwater biodiversity requires global collaboration to reconcile human needs with ecological integrity, ensuring these vital systems endure for future generations. Failure to act risks irreversible losses to biodiversity and the ecosystem services underpinning human well-being.

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