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Safeguarding freshwater biodiversity and resilient social-ecological systems in uncertain futures

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Freshwater ecosystems and their diverse plant and animal communities are neglected, under-appreciated and threatened by the multiple interacting stressors of the Anthropocene era. Climate change is the most ominous threat on the horizon and freshwater ecosystems are particularly vulnerable. Climate change, multiple stressor syndromes and other uncertainties challenge freshwater restoration and conservation. This perspective presents a brief summary of major gaps in knowledge, governance and implementation that inhibit efforts to protect and restore freshwater biodiversity and offers guidance to address major gaps. The mission for freshwater science over the next decade is to leverage robust scientific knowledge, governance, funding and policy to inform freshwater restoration and conservation action plans (e.g., the Emergency Recovery Plan, GBF 30 × 30, SDGs, The Freshwater Challenge), and even to exceed their present targets, while simultaneously safeguarding resilient social-ecological systems and human wellbeing under climatic and other uncertainties.

KEYWORDS

biodiversity, freshwater ecosystem services, multiple stressors, climate change, rehabilitation, conservation, social-ecological resilience

Fresh water is life and wellbeing for all lifeforms on Earth (One Health[1]). People use and enjoy freshwater biodiversity and benefit from the ecosystem services provided by healthy aquatic ecosystems–food and other material goods, cultural services and environmental regulation (Lynch et al., 2023). Yet freshwater ecosystems and their diverse plant and animal communities are neglected, under-appreciated and threatened by the multiple interacting stressors of the Anthropocene era (Albert et al., 2021; Dudgeon and Strayer, 2025). Shameful statistics on freshwater biodiversity loss abound. One-quarter of decapod crustaceans, fishes and odonates on the IUCN Red List of Threatened Species[2] are threatened with extinction (Sayer et al., 2025), and many more species not yet assessed are likely to be suffering declining health and population losses. Prevalent threats driving population declines and species extinctions present a devastating catalogue (Reid et al., 2019; Tickner et al., 2020). Although there are many examples of restoration successes, typically but not always at local scales (e.g., Pander et al., 2015), land and water management systems are largely failing to address today's complex and spatially dispersed syndromes of

1. https://www.who.int/health-topics/one-health#tab=tab_1

2. https://www.iucnredlist.org/

freshwater ecosystem degradation. Even our freshwater protected areas are poorly buffered against pressures within and external to their boundaries (Acreman et al., 2020). Climate change is dumping a further blanket of pressures on freshwater systems and already compounds multiple-stressor problems.

Since its inception in 2016, the Freshwater Science section of *Frontiers in Environmental Science* has set out grand challenges facing the field (Bunn, 2016; Arthington, 2021). The section promotes opportunities offered by the Sustainable Development Goals (SDGs)[3], the post-2020 Kunming-Montreal Global Biodiversity Framework (GBF)[4] and the 2021–2030 UN Decade on Ecosystem Restoration[5] to bring the linkages between terrestrial, freshwater and estuarine/marine biodiversity, ecosystem integrity and human health/wellbeing (One Health) into public prominence.

The GBF provides a vital policy setting and ambitious targets for the restoration, effective conservation and management of 30% of inland waters by 2030, with emphasis on maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people (CBD, 2022).

This long overdue recognition of 'inland water' ecosystems and the freshwater biodiversity crisis within a unique global policy has resonated widely. It is critically informed by the publication of a freshwater biodiversity Emergency Recovery Plan - ERP (Tickner et al., 2020) setting out six major priorities for global action and policy development to "bend the curve of freshwater biodiversity loss" including: (1) accelerate implementation of environmental flows; (2) improve water quality to sustain aquatic life; (3) protect and restore critical habitats; (4) manage exploitation of freshwater species and riverine aggregates; (5) prevent and control nonnative species invasions in freshwater habitats; and (6) safeguard and restore freshwater connectivity.

The ERP is supported by a suite of 'evidence-based roadmap' reviews to guide effective implementation of each action theme in diverse contexts around the world. Example reviews include accelerating environmental flow implementations (Arthington et al., 2024) and safeguarding and restoring freshwater connectivity within and among freshwater systems and their landscape and seascape surroundings (Thieme et al., 2024). These implementation reviews are also valuable for their clear enunciation of the many practical, societal and policy factors that enable (or inhibit) freshwater restoration and conservation actions in context (e.g., Twardek et al., 2021).

The ERP blueprint has received remarkable support from freshwater scientists, conservation practitioners and many other sectors with support growing apace. Might it prove to be the 'last best hope' for recovery and conservation of freshwater biodiversity globally? Dudgeon and Strayer (2025) hope so, but they caution that successful implementation of all ERP recommendations will require significant effort on emerging, overlooked or poorly understood topics. Their analysis of impediments to successfully 'bend the curve of biodiversity loss' offers many insights and a positive but tempered conclusion.

A recent exploration of major knowledge gaps in freshwater science, deficiencies of governance and legislation, and impediments to practical freshwater restoration and conservation is revealing (van Rees et al., 2025). Prominent gaps include patchy biodiversity inventory (e.g., taxonomic deficits, neglected ecosystems, geographic bias), unresolved multiple stressor and climate change interactions, limited monitoring and weak evidence of restoration and conservation outcomes, poor stakeholder and Indigenous participation in knowledge generation and collaborative management, and weaknesses in navigating trade-offs between water uses for societal development and priorities for freshwater biodiversity.

Every one of these gaps has the potential to influence our capacity to meet the 30 × 30 restoration and conservation targets of the Kunming-Montreal Global Biodiversity Framework, and related initiatives (van Rees et al., 2025). Furthermore, the deadline for achievement of GBF goals for all signatory countries and ecosystem types (see Keith et al., 2022) is frighteningly close.

Climate change is the most ominous threat on the horizon and freshwater ecosystems are particularly vulnerable. Shifting thermal and water quality/quantity regimes directly impact aquatic species and compound the impacts of other stressors on freshwater biodiversity and ecosystem services (Capon et al., 2021). Human population growth will vastly increase demands for fresh water and new water infrastructure, typically depriving aquatic systems of habitat, connectivity pathways and essential ecological cues. Uncertainty related to the societal and ecological implications of climate change combined with other threats means that our concept of ecosystem restoration to a former preferred (or near natural) state is often inappropriate, and rarely feasible, given the magnitude of changes and degradation of most of today's freshwater ecosystems, and the emergence of hybrid and novel ecosystems that support valued biodiversity (Erős et al., 2023). For example, our current practice of targeting environmental flows (e-flows) towards restoration of historic natural flow patterns (the 'natural flow regime paradigm') is shifting towards the goal of managing for social-ecological resilience in an adaptive management framework that explores trade-offs and embraces learning and adjustment of goals and practices as outcomes emerge over time (Poff et al., 2016; Poff, 2018).

Thoms and Fuller (2024) promote social-ecological resilience thinking, and "rehabilitation" as the preferred terminology for efforts to sustain and protect robust, diverse and functional freshwater ecosystems under situations of future environmental and sociological uncertainty. Future-proofing the freshwater Emergency Recovery Plan sets out options and opportunities to safeguard ecosystems against future environmental and sociological uncertainties and build ecosystem resilience to shocks and surprises (Lynch et al., 2024). Nature-based Solutions (NbS)[6] and Green or Natural Infrastructure address major societal challenges (such as flood and drought mitigation) and human wellbeing while simultaneously enhancing the biodiversity and resilience of ecosystems, their capacity for renewal and provision of services. Specific NbS can be qualitatively linked to several of the six

3. https://sustainabledevelopment.un.org/sdgs

4. https://www.cbd.int/doc/c/409e/19ae/369752b245f05e88f760aeb3/wg2020-05-l-02-en.pdf

5. https://www.decadeonrestoration.org/about-un-decade

6. https://iucn.org/our-work/nature-based-solutions

conservation goals of the freshwater biodiversity Emergency Recovery Plan (Tickner et al., 2020) in win-win contexts (van Rees et al., 2023). However, applications of trade-off procedures (e.g., Thieme et al., 2021; Opperman et al., 2023) during NbS practice and biodiversity conservation planning are limited and warrant far more attention. van Rees et al. (2025) call for integration of conservation practice/ ecological knowledge with Integrated Water Resources Management as a promising avenue for addressing trade-offs between human and ecological water needs. The broadest goals of Target three of the Global Biodiversity Framework relate to area-based conservation targets to achieve "ecologically representative, well-connected and equitably governed systems of protected areas", while "recognizing and respecting the rights of Indigenous peoples and local communities" (CBD, 2022). Biodiversity knowledge co-production and respectful engagement with stakeholders, Indigenous peoples and local communities will be critical to achieving these ambitious GBF conservation goals.

Leveraging robust scientific knowledge, governance, funding and policy to inform freshwater restoration and conservation action plans (e.g., ERP, GBF 30 × 30, SDGs, NbS, The Freshwater Challenge[7]), and even to exceed their present targets, while simultaneously safeguarding resilient social-ecological systems and human wellbeing under climatic and other uncertainties, is our outstanding mission for the next decade.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AA: Project administration, Investigation, Conceptualization, Writing – review and editing, Writing – original draft.

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7. https://www.freshwaterchallenge.org/

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