Environmental Reviews

OPEN ACCESS | Review

Future-proofing the emergency recovery plan for freshwater biodiversity

Abigail J. Lynch [a], Amanda A. Hyman [b], Steven J. Cooke [c], Samantha J. Capon [d], Paul A. Franklin [e], Sonja C. Jähnig [f,g], Matthew McCartney [h], Nguyễn Phú Hòa [i], Margaret Awuor Owuor [j,k,l], Jamie Pittock [m], Michael J. Samways [n], Luiz G. M. Silva [o], E. Ashley Steel [p], and David Tickner [q]

[a]United States Geological Survey (USGS), National Climate Adaptation Science Center, 12201 Sunrise Valley Drive MS 516, Reston, VA 20192, USA; [b]Department of Biological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA; [c]Department of Biology, Canadian Centre for Evidence-Based Conservation, Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, ON K1S 5B6, Canada; [d]Australian Rivers Institute, Griffith University, Nathan, Queensland 4101, Australia; [e]National Institute of Water and Atmospheric Research, Gate 10 Silverdale Road, Hamilton 3216, New Zealand; [f]Leibniz Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, Berlin, Germany; [g]Humboldt-Universität zu Berlin, Geography Department, Berlin, Germany; [h]International Water Management Institute, PO Box 2075, Colombo, Sri Lanka; [i]Nong Lam University, Ho Chi Minh City, Vietnam; [j]Wyss Academy for Nature at the University of Bern, Kochergasse 4, 3011 Bern, Switzerland; [k]Institute of Ecology and Evolution, Baltzerstrasse 6, 3012 Bern, Switzerland; [l]South Eastern Kenya University, Kitui 170-90200, Kenya; [m]Fenner School of Environment and Society, The Australian National University, 48 Linnaeus Way, Acton ACT 2600, Australia; [n]Department of Conservation Ecology and Entomology, Stellenbosch University, Matieland 7602, South Africa; [o]ETH-Zurich, Institute of Environmental Engineering, Stefano-Franscini-Platz 5, Zürich 8093, Switzerland; [p]School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, USA; [q]WWF-UK, Living Planet Centre, Woking, UK

Corresponding author: **Abigail J. Lynch** (email: ajlynch@usgs.gov)

Abstract

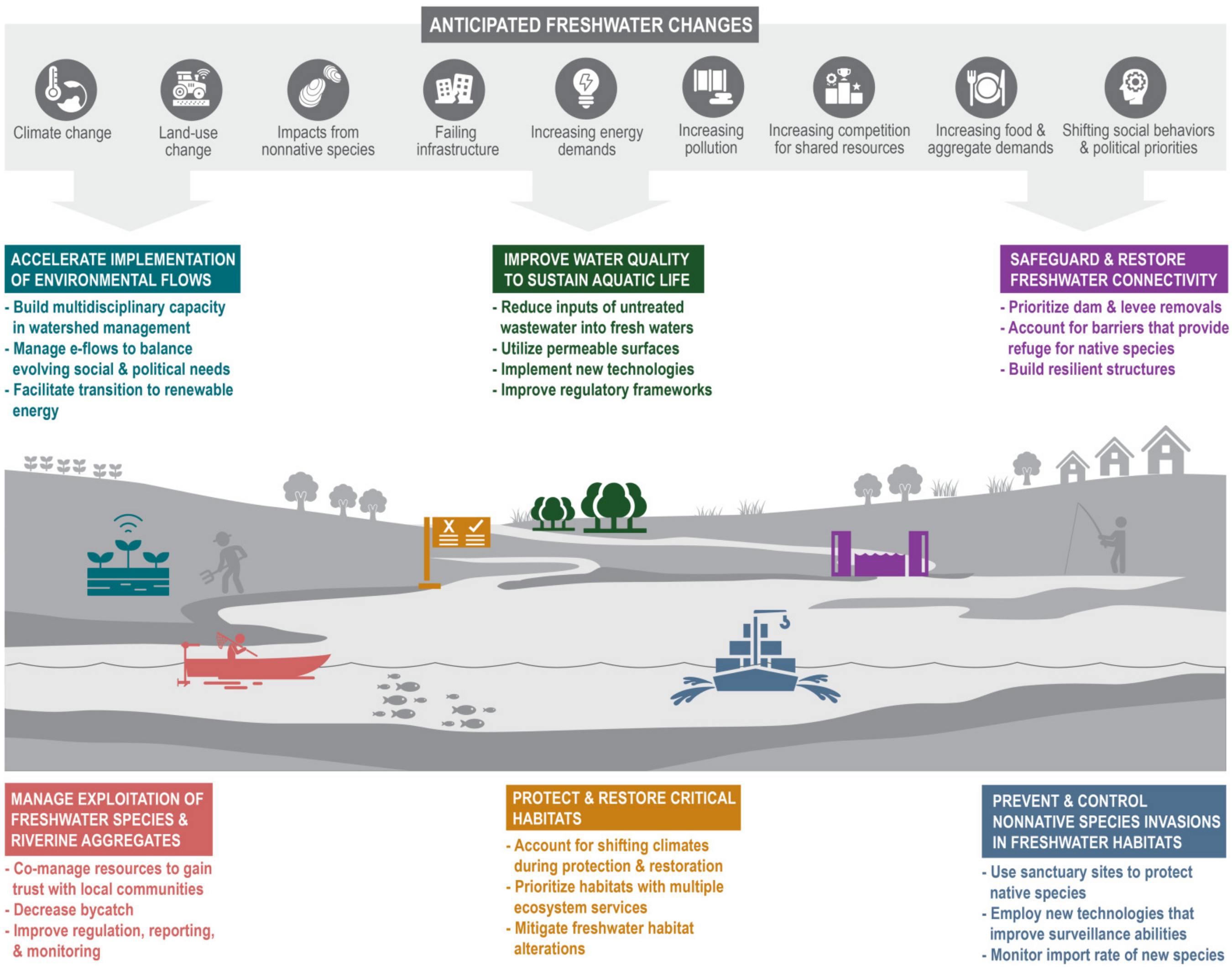
Freshwater biodiversity loss is accelerating globally, but humanity can change this trajectory through actions that enable recovery. To be successful, these actions require coordination and planning at a global scale. The Emergency Recovery Plan for global freshwater biodiversity aims to reduce the risk for freshwater biodiversity loss through six priority actions: (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. These actions can be implemented using future-proofing approaches that anticipate future risks (e.g., emerging pollutants, new invaders, and synergistic effects) and minimize likely stressors to make conservation of freshwater biodiversity more resilient to climate change and other global environmental challenges. While uncertainty with respect to past observations is not a new concern for freshwater biodiversity, future-proofing has the distinction of accounting for the uncertainty of future conditions that have no historical baseline. The level of uncertainty with respect to future conditions is unprecedented. Future-proofing of the Emergency Recovery Plan for freshwater biodiversity will require anticipating future changes and developing and implementing actions to address those future changes. Here, we showcase future-proofing approaches likely to be successful using local case studies and examples. Ensuring that response options within the Emergency Recovery Plan are future-proofed will provide decision makers with science-informed choices, even in the face of uncertain and potentially new future conditions. We are at an inflection point for global freshwater biodiversity loss; learning from defeats and successes can support improved actions toward a sustainable future.

Key words: climate change, freshwater conservation, freshwater ecosystems, freshwater life, uncertainty

Freshwater biodiversity at risk

Freshwater biodiversity is essential to human well-being and livelihoods (Lynch et al. 2023) and it is at risk (Reid et al. 2019). Human settlements have had a strong association with freshwater systems since the earliest civilizations (e.g., Egyptian settlements around the Nile River, Mesopotamia settlements situated within the Tigris–Euphrates river system, and Chinese Neolithic settlements in the middle Yangtze River basin; Jähnig et al. 2022). Because of these associations and an ever-growing demand on freshwater resources to support food, water, sanitation, and transportation routes, humans have a long history of impacting freshwater systems and freshwater biodiversity. Current and emerging threats include land-use change, new types of contaminants and

Fig. 1. Example of response options for future-proofing the six key actions of the Emergency Recovery Plan for freshwater biodiversity to current and emerging stressors. River cross-section base layer courtesy of Tracey Saxby, Integration and Application Network (ian.umces.edu/media-library).



increased pollutants, unsustainable harvest, nonnative species introductions, and climate change (Fig. 1). Resulting impacts include floodplain loss (EEA 2020), reduction of connectivity (Grill et al. 2019), declining freshwater vertebrate and invertebrate populations (Goulson 2019; Montgomery et al. 2020; WWF 2022), and shifting species distributions (Heino et al. 2020; Wang et al. 2021).

The Emergency Recovery Plan for global freshwater biodiversity (Tickner et al. 2020) is predicated on established assessments of prevailing and emerging threats to freshwater habitats, flora, and fauna (e.g., Dudgeon et al. 2006; Reid et al. 2019). It is framed around six key actions to "bend the curve" of global freshwater biodiversity loss: (1) accelerating implementation of environmental flows; (2) improving water quality; (3) protecting and restoring critical habitats; (4) managing the exploitation of freshwater ecosystem resources, including individual species and riverine aggregates; (5) preventing and controlling nonnative species invasions; and (6) safeguarding and restoring river connectivity (see Arthington et al. in press; Ormerod et al. in press; Piczak et al. 2023; Cooke et al. in press; Britton et al. in press; Thieme et al. 2023, for more on each action).

Implementation of response options within these six key actions is often challenging (Tickner et al. 2020; Arthington 2021) for a variety of reasons linked to uncertainty in political priorities (e.g., Hermoso 2017), technical capacity (Di Marco et al. 2017), data availability (Stoffels et al. 2021), research gaps (Harper et al. 2021), funding constraints (e.g., Cracknell et al. 2016), and the occurrence of trade-offs between aiding recovery of freshwater biodiversity and other imperatives, such as appeasing diverse partners (Paterson-Shallard et al. 2022) and human food security. In addition, the uncertainty related to climatic, demographic, geopolitical, socio-economic, and cultural context is high because of the lack of historical baselines. Freshwater ecosystems and biodiversity are at particular risk when these uncertainties are ignored because of their reliance on processes that occur remotely and over vast spatial extents and the direct relationship to climate factors that are predicted to change, become more extreme, and decouple (e.g., temperature, precipitation, and snowpack). These factors can lead to unprecedented uncertainty and unprecedented conditions.

In this paper, we discuss how the six priority actions within the Emergency Recovery Plan for global freshwater biodiversity can be implemented with approaches that anticipate future risks (e.g., emerging pollutants and invasive species) and minimize likely stressors to make conservation of freshwater biodiversity more resilient to climate change and other global environmental challenges. We highlight key drivers to consider and approaches likely to be successful using local case studies and examples. Ensuring that response options within the Emergency Recovery Plan are future-proofed will provide decision makers with science-informed choices, even in the face of uncertainty. We hope to inform conservation, restoration, and water use practices.

Future-proofing for freshwater biodiversity

Though uncertainty has long been a consideration for freshwater biodiversity conservation (e.g., Hermoso and Kennard 2012), uncertainty related to unprecedented futures requires a new framing because all prior measures of success (e.g., restoration to historical conditions) no longer apply (Matthews 2022). Previous approaches to protecting freshwater biodiversity relied on the assumptions that the future will be similar to the past (Tonkin et al. 2019) or on most likely future conditions. Now, with changes in land use, direct exploitation of organisms (e.g., overfishing), climate change, pollution, and invasive species (IPBES 2019), possible future conditions exceed the range of historical variability (IPCC 2022*a*). Backwards-looking approaches that rely only on historical (and often stationary) references as benchmarks to design and evaluate ecological interventions risk dangerously perverse outcomes by constraining possible adaptive responses of species (e.g., range shifts) and ecosystems (e.g., phase shifts) (Magness et al. 2022). New conditions for which there is no precedent make conventional conservation and restoration objective targets not only irrelevant but potentially maladaptive (Barnett and O'Neill 2010). For example, new conditions may be created both by extremes in any dimension of the system (e.g., flow or temperature) and also by the decoupling of physical or biological phenomena (e.g., warmer temperatures that are associated with higher flows rather than lower flows or low food resources during flows where food resources had previously been high). If management interventions do not anticipate these possible suites of future conditions, desired environmental outcomes may not be achieved. This is not to say that management approaches should not build from lessons of the past but rather that new, robust, and flexible strategies are needed to handle whatever may transpire in the future.

The concept of "future-proofing" centers on this important intention of explicitly addressing future uncertainty. Future-proofing refers to the process of anticipating future events under unprecedented levels of uncertainty and including unprecedented conditions and developing methods to mitigate or minimize plausible stressors and shocks to a system (Rehman et al. 2017). The first step in future-proofing is the reasonable anticipation of a range of possible future events that may impact the domain of interest. This can include monitoring, experiments, and modeling to identify plausible ecological trajectories (Crausbay et al. 2022). The second step involves developing and implementing actions to reduce the impact of anticipated possible future changes. This can include monitoring, pilot studies, and portfolio approaches to buffer against a range of plausible trajectories (Lynch et al. 2022). Both these steps help reset expectations for future outcomes.

The principles of future-proofing have been explored across multiple sectors, including governance, business (Manu 2021), infrastructure/construction (Masood et al. 2016; UNEP 2021), and environmental law (Gupta and Schmeier 2020). Future-proofing is increasingly being applied in ecological and environmental domains to account for anticipated future environmental change. Challenges like sea-level rise (Mazor et al. 2021), maintenance of natural hydrological processes an.d water quality (Crossman et al. 2013), and mitigation of soil degradation and loss in the face of storms (Marden 2004) are being addressed through future-proofing. Future-proofing protected areas has involved dialogue-based, multi-stakeholder processes that recognize the threat of ongoing climate change while developing effective systems for governance and management (van Kerkhoff et al. 2019; also see Box 1). Many types of restoration activities have contributed to future-proofing ecosystems by improving the ecosystem's resilience to future risks (O'Briain et al. 2017; Timpane-Padgham et al. 2017; Wood et al. 2019; Wu et al. 2020; Frietsch et al. 2023). Future-proofing has also been used to help maintain genetic diversity, for example, in mammal populations (Lott et al. 2022) and to conserve insect diversity (Samways 2020).

In essence, future-proofing is designed to safeguard against future known uncertainties (e.g., climate change and emerging pollutants) and build resiliency to withstand future unknown uncertainties (e.g., unexpected invasive species, algal blooms, and diseases) and unanticipated surprises. It is a bet-hedging approach to build adaptive capacity and enhance a system's ability to respond to future change (Frietsch et al. 2023). Because change is an ongoing process, future-proofing encourages strategies that are flexible and increasingly refined and redirected over time. Iterative adjustment is needed because of the possible, even likely, increase in the range of threats, intensity of stressors, and unanticipated interactions among them. For example, in Sweden, while extreme weather will be a dominant driver over the next few decades, risks relating to high sea-level rise will take precedence toward the end of this century (Hieronymus and Kalén 2022). In this example, the prominence of each driver in decision processes will vary with its relative importance at each time point. This adaptive process can be assisted by both new technologies (e.g., satellite imagery, machine learning, and environmental DNA) and better analysis to be as anticipatory and nimble as possible.

BOX 1. Case study: future-proofing freshwater biodiversity associated with protected areas in South Africa

South Africa has three globally recognized biodiversity hotspots (Mittermeier et al. 2005). Although mostly a dry region, it is rich in localized endemic freshwater species, mainly in mountainous areas. Despite most of the feeder streams originating in protected areas at higher elevations, many of these species are under threat from human activity (Darwall et al. 2011). To future-proof this biodiversity, protected areas required more resilience by spatially extending beyond just higher elevation feeder streams. This was done by instigating large networks of indigenous remnant areas of land and water as conservation corridors to protect water bodies across timber plantation–natural area mosaics (Box 1 Figure A). The water bodies include springs, streams, rivers, and wetlands (Box 1 Figure B). The included marshy areas and damp, hydromorphic soils delimit the expansion of timber plantations into the natural areas (Samways and Pryke 2016).

Well-managed freshwater protected areas can play an important role in maintaining historical levels of biodiversity. However, these protected areas are essentially pockets in the wider matrix of human activity, subject to adverse effects, not least extreme weather events. The strategically developed networks of conservation corridors in South Africa maintain clean water flow and standing water for organisms to sustain themselves while importantly giving them the option to move when local habitat conditions become sub-optimal, which can extend the effectiveness of protected areas in, for example, agroforestry production areas (Pryke and Samways 2012).

The corridor networks were future-proofed by ensuring that functional connection was instigated, maintained, and tested at a regional scale through the joining of networks of the many plantation mosaics. The networks embrace all local topographies to provide ecological resilience according to the future-proofing principles of insect conservation, which includes many other functional components of biodiversity, from indigenous plants to the megafauna (Samways 2015). The networks can support high levels of spatial heterogeneity, providing a diverse portfolio of habitats to buffer the system against the inevitable shocks from climate change and other stressors (Samways and Pryke 2016). Using freshwater insects, such as “riverflies” (Ephemeroptera/Plecoptera/Trichoptera) and dragonflies (Odonata), as sensitive indicators of freshwater condition, networks of conservation corridors maintain running and standing freshwater ecological integrity and heterogeneity and are more resilient, compared with major protected areas as the reference condition (Kietzka et al. 2015, 2019, 2021).

Box 1 Figure A. A conserved wetland and its catchment in a nonnative timber plantation mosaic. The wetland is part of a network of large, interconnected conservation corridors aimed at providing ecological resilience in the face of future climate change. Photo credit: Michael Samways.

Environ. Rev. **00:** 1–16 (2023) | dx.doi.org/10.1139/er-2022-0116

Box 1 Figure B. A remnant native grassland-stream corridor adjacent to a protected area over the horizon. The pine trees are nonnative and grown for timber. Photo credit: Michael Samways.

Anticipating future freshwater changes

Future-proofing does not replace existing ecological paradigms but rather is an approach to manage freshwater resources by assuming high levels of uncertainty in future conditions, drawing from these ecological paradigms to inform strategies as appropriate. The stressors on biodiversity vary greatly among freshwater ecosystem types and spatial scales (Reid et al. 2019). Much remains unknown about how stressors might interact to influence taxonomic and functional biodiversity or abiotic components of freshwater systems (Feio et al. 2022; Vos et al. 2023). Additionally, how society chooses to respond to global environmental changes can inadvertently interact with and exacerbate impacts on freshwater ecosystems and potentially lead to maladaptation (Barnett and O'Neill 2010). Changing values and shifting societal attitudes can alter decision trajectories (Daly and Farley 2010; Speed et al. 2016; also see Box 2). Future-proofing the Emergency Recovery Plan will involve considering how plausible future drivers, such as climate change, population growth, and new pollutants, can be accounted for in designing and implementing each of the six priority actions to protect and restore freshwater ecosystems (Fig. 1). Vast threats and sources of uncertainty impact the current and future viability of freshwater biodiversity as highlighted across response options for each of the six priority actions (see Arthington et al. in press; Ormerod et al. in press; Piczak et al. 2023; Cooke et al. in press; Britton et al. 2023; Thieme et al. 2023, for more on each action). Managers, however, can anticipate some future freshwater changes; there are examples from around the world of how future-proofing strategies are already being implemented. Future-proofing can be integrated into other existing planning processes, so many of these examples reflect broader natural resource best management practices (Table 1). The important distinction, however, is that future-proofing frames these actions by specifically acknowledging future uncertainties and a range of possible future conditions.

Climate change paired with growing human use of freshwater threatens sustainable environmental flows (Arthington et al. in press). Climate change exacerbates existing stressors on freshwater ecosystems by altering precipitation and river flow regimes. Shifting precipitation frequency and amounts can cause both flooding and droughts, making waterways in-

BOX 2. Case study: future-proofing co-management of Waikato River, New Zealand

The Waikato River is one of the most economically significant rivers in Aotearoa New Zealand and highly valued by indigenous Māori, for whom the river provides spiritual sustenance and critical resources (Box 2 Figure A; Collier et al. 2010; Te Aho 2010). The river is subject to intense pressures, including land-use change and intensification, damming and flow regulation, flood control works, nonnative species invasion, plus sand and gravel extraction (Box 2 Figure B; Collier et al. 2019). These pressures have degraded the ecological state of the river with the majority of monitoring sites continuing to show deteriorating trends in macroinvertebrate metrics (Waikato River Authority 2021) and depauperate native fish communities (Hanchet 1990; Collier et al. 2019; Pingram et al. 2021).

The failure to halt and reverse declines in the state of the river has been attributed to decision makers favoring economic growth over river-centered values when balancing multiple interests (Te Aho 2019). However, evolving relationships between government and indigenous Māori are driving fundamental changes in how fresh waters are managed in Aotearoa New Zealand (Harmsworth et al. 2016; Te Aho 2019). This is resulting in a new co-governance and co-management regime for the Waikato River.

The Waikato–Tainui Raupatu Claims (Waikato River) Settlement Act 2010 ushered in a new Vision and Strategy (Waikato River Authority 2008) that requires the restoration and protection of the river's health and well-being. It is explicitly intergenerational and embeds the Māori concept of *kaitiakitanga*—guardianship of the environment for both its own sake and for present and future generations to use and enjoy (Te Aho 2019). Achieving the Vision and Strategy within this intergenerational framing necessitates anticipation of both current and, importantly, future pressures and the socio-ecological context in which they exist. As such, giving effect to the Vision and Strategy in regional planning processes has required explicit recognition of an 80-year timeframe to achieve the objectives of the Vision and Strategy (Waikato Regional Council 2020) and thus established a need to account for future uncertainty in contemporary decision making.

Box 2 Figure A. An aerial view of Huka Falls on the upper reaches of the Waikato River shortly after it flows out of Lake Taupō, New Zealand. Photo credit: NIWA/Dave Allen.

Environ. Rev. **00:** 1–16 (2023) | dx.doi.org/10.1139/er-2022-0116

Box 2 Figure B. Karapiro dam is the last in a series of seven hydropower dams along the Waikato River, New Zealand. These dams have a significant influence on the flow regime and character of the river and its ecology. Photo credit: NIWA/Lana Young.

hospitable to biodiversity and leaving them susceptible to dangerous algal blooms (Chapra et al. 2017), mass fish mortality events (Lacerda Macêdo et al. 2021), and shifts in species distributions through time (Comte and Grenouillet 2013). In addition to climate change, aspects of biodiversity are forgotten (Lim 2014) when efforts are focused on allocating water across human users (Vörösmarty et al. 2010; Arthington et al. in press). In Australia, for instance, there is growing concern that unmanaged "risks to shared water resources" cause diminishing flows due to expansion of on-farm dams, diversion to other irrigation priorities, afforestation, forest fires, poor groundwater management, and climate change (Van Dijk et al. 2006). In 2012–2019, independent of climatic variation, observed flows in the River Murray, Australia, were a fifth lower than expected by management models (Wentworth Group of Concerned Scientists 2020). Accounting for such uncertainties and focusing on broad objectives to avoid perverse outcomes are both part of future-proofing environmental flows.

Reducing pollution and mitigating its effects will be key for freshwater biodiversity (Ormerod et al. in press). Water managers can sometimes focus more readily on regulating direct water withdrawals and point source pollution because they have more agency to control it, for example, through permitting requirements and penalties (Loucks and van Beek 2016). With growing demand for food and energy paired with increasing amounts of wastewater, however, diffuse sources are becoming greater concerns, such as those from food and fiber production or from expanding urban landscapes (Ormerod et al. 202X). This is especially concerning in areas that may experience droughts and decreased precipitation because pollutants will be less diluted. Reducing diffuse agricultural pollution requires a combination of improved catchment management, incentives that encourage sustainable practices, and improved environmental standards (Bieroza et al. 2021). The regulation and mitigation of diffuse urban sources, particularly emerging contaminants (e.g., microplastics and pharmaceuticals), will be equally important to future-proof water quality. Future-proofing water quality in urban settings can be achieved through a variety of means, such as modernizing urban drainage systems, investment to replace aging sewer infrastructure, and updating regulations that address new pollution challenges (e.g., see Halleux 2023).

Table 1. Select examples of anticipated future freshwater changes, future-proofing strategies to address them, and on-the-ground implementation for priority actions in the Emergency Recovery Plan for freshwater biodiversity.

	Anticipated future freshwater changes	Future-proofing strategies	Examples of implementation	References
Action 1: accelerating implementation of environmental flows	Increasing competition for shared resources	• Build capacity in watershed management and multi-disciplinary work specifically considering future conditions and needs	In Alberta, Canada, the Peace–Athabasca Delta e-flows project is integrating traditional ecological knowledge from 11 Indigenous governments	Candler et al. (2010); Parlee (2011)
	Shifting social/political priorities	• Manage e-flows as part of integrated solutions for multiple interacting stressors in river basins to balance evolving social and political needs	The National Policy Statement for Freshwater Management in New Zealand created and implemented a hierarchy of obligations, stating that the health and well-being of the water body must be considered first, before human health, and then economic benefits. The policy also explicitly requires consideration of climate change in setting limits	Craig et al. (2017); New Zealand Government (2020)
	Increasing energy demands	• Facilitate the transition to renewable energy while having minimal impacts on freshwater ecosystems	Queensland, Australia, is planning the world's largest pumped hydro scheme as part of a new energy plan to lower emissions, moving away from coal and gas to renewable energy, including wind and solar	Gilfillan and Pittock (2022)
Action 2: improving water quality	Increasing wastewater	• Reduce inputs of untreated wastewater into freshwater ecosystems • Reduce discharge from combined sewer overflows • Utilization of permeable surfaces • Use and implementation of new technologies	The sponge city concept was developed to address China's rapid urbanization and associated water-quality issues and water shortages. The concept includes increased permeable surfaces within cities and a division of rainwater and sewage pipe networks to reduce water pollution	Liu et al. (2017); Cook et al. (2019)
	Increasing non-point pollution	• Improve regulatory frameworks	The EU's Green deal, in complement with Water Framework Directive, seeks to reduce diffuse agriculture pollution	Bieroza et al. (2021)
Action 3: protect and restore critical habitats	Species range shifts	• Prioritize protecting intact habitat • Account for shifting climates during protection and ecological restoration	The Bita River in Colombia was made a protected conservation area, reflecting its ecological, social, and cultural importance based on extensive biological surveys, future scenario modeling, and support from local communities. In 2018, it was designated a Ramsar site	Suárez et al. (2021)
	Increasing competition for shared resources	• Prioritize restoration and preservation of habitats with multiple ecosystem services • Provide market incentives for ecosystem services • Encourage multi-partner collaborations	The Nature Conservancy's Water Funds includes 32 initiatives across South America that conserve land, reforest land, and/or pay local farmers and ranchers to protect riverside forests on their land to ensure clean downstream drinking water.	TNC (2022)
	Land-use change	• Ensure that freshwater habitat alterations are mitigated or off-set	Colombia has implemented environmental compensation under the National Policy for Integral Management of Biodiversity and its Ecosystem Services	Mendoza et al. (2020)

Table 1. (*concluded*).

	Anticipated future freshwater changes	Future-proofing strategies	Examples of implementation	References
Action 4: manage exploitation of freshwater species and riverine aggregates	Increasing demands for biological resources	• Co-manage resources to gain trust with local communities • Use harvest and control efforts to mitigate overexploitation • Decrease bycatch and mitigate associated mortality	Co-management of the fishery in Tonle Sap, Mekong River, Cambodia, has empowered fishers, improved floodplain protection, and increased biodiversity and household catch simultaneously	Phang et al. (2019)
	Increasing aggregate demands	• Decrease demand; recycle and repurpose waste aggregates • Improve regulation, reporting, and monitoring • Strengthen and develop governance systems	In Singapore, eco-green buildings use concrete that is derived purely from recycled waste aggregates	Silva et al. (2019)
Action 5: prevent and control nonnative species invasions in freshwater habitats	Worsening impacts from existing nonnative species	• Increase resilience of native species through active management and habitat improvement • Utilize sanctuary or "ark" sites to protect native species threatened until technologies improve to control and eradicate invasive species • Develop and employ new technologies that improve detection and eradication • Legislation to enable effective control techniques (including lethal)	Two pheromones have shown promise to aid in the control and eradication of nonnative sea lampreys in North America's Laurentian Great Lakes	Simberloff (2021)
	Introduction and establishment of new nonnative species	• Develop and employ new technologies that improve surveillance abilities • Model dispersal mechanisms and anticipated species interactions • Legislation and regulation of trades and markets involving nonnative species	Environmental DNA is a noninvasive method to detect nonnative freshwater species. It has been used to detect silver and bighead carp at the invasion frontier in the Mississippi River basin in the USA, north of electric barriers used to deter fish passage	Jerde et al. (2011)
	Shifting human behavior	• Survey consumer preferences • Monitor species availability and the import rate of new species	Monitoring the ornamental crayfish trade in Germany showed that approximately 10 years after a "crayfish hype", reduced species diversity available from online shops was observed. The rate of import of new species had decreased and approached pre-hype values	Chucholl and Wendler (2017)
Action 6: safeguard and restore freshwater connectivity	Failing infrastructure	• Prioritize removals to improve connectivity for native species • Account for barriers that provide refuge for native species from invasive species • Build structures resilient to extreme events	Following an extreme flooding event (>100-year flood from Hurricane Irene) on the White River in the USA, an interagency team identified and prioritized failed culverts and road crossings. To prevent such costly damages in the future, many were converted to bridges, upgraded with new technology and designs, and/or improved to handle larger floods	Gillespie et al. (2014)
	Increasing extreme events	• Build structures resilient to extreme events	In Germany, the Elbe River Levee Setback project worked to restore the Elbe's floodplain, in part by removing and relocating levees	Serra-Llobet et al. (2022)
	Increasing energy demands	• Facilitate the transition to renewable energy while having minimal impacts on freshwater ecosystems	Modeling of future energy expansion in Chile has shown that Chile could meet its low-carbon power targets without damming any more free-flowing rivers, with minimal impact on system cost	Opperman et al. (2023)

Reversing land conversion from development, improving agricultural practices, targeting restoration, and providing forward-looking protection of critical habitat, specifically, will be vital for future-proofing freshwater biodiversity (Piczak et al. 2023). Land-use change and degradation of terrestrial ecosystems, particularly for agriculture, cause degradation of freshwater ecosystems (Tilman 1999). Eighty-six percent of land-use change globally is for agriculture (Winkler et al. 2021), and 70% of water extracted from freshwater ecosystems globally is used in agriculture (FAO 2022). Restoration of environmental components can be focused on process-based approaches, targeted at the root causes of ecosystem changes (Beechie et al. 2010). More systemic networks of protected areas and other effective area-based conservation measures can also increase resiliency and future-proof critical habitats for uncertain outcomes (Cid et al. 2022; Worthington et al. 2022; also see Box 1).

Inland fisheries are complex and often difficult to manage due to political, economic, and human behavioral drivers (Allan et al. 2005; Cooke et al. in press). Overharvesting, especially when combined with destructive fishing methods and unsustainable aggregate extraction (e.g., sand and gravel mining), can have devastating consequences on freshwater fisheries and aquatic ecosystems (WWF 2022). Climate change may also influence societal settlement patterns, altering pressures on fisheries and aggregate resources. While conflict between fishing and freshwater biodiversity conservation does exist, often there are bigger and shared threats to both (e.g., connectivity, pollution, and flow). Importantly, both benefit from addressing these shared threats. For example, a community and government co-management effort for fishery and conservation in the Tonle Sap, Mekong River, Cambodia, has empowered fishers in management, improved floodplain protection, and increased resident fish biodiversity and household fish catches (Phang et al. 2019, and references therein). Freshwater biodiversity supports resilient aquatic systems that, in itself, helps future-proof sustainable fisheries and aquaculture (COFI 2022).

Deliberate or accidental introduction of nonnative aquatic species—which establish invasive populations that compete with native species for resources—is considered as one of the most insidious threats to freshwater ecosystems globally (Britton et al. 2023). Shifting human behaviors (e.g., consumer preferences for plants and companion animals through the ornamental trade; massive water-transfer projects) and interactions of nonnative species with other nonnative species (e.g., invasional meltdown; Ricciardi and MacIsaac 2000; Emde et al. 2012), in addition to the effects of changing conditions (e.g., altered patterns of precipitation leading to biosecurity lapses at aquaculture facilities or increased suitable habitat for nonnatives), can all lead to novel introduction pathways, dispersal mechanisms, and ecological impacts. Introduction and spread of nonnative invasive species under changing climates will likely have unpredictable and far-reaching impacts on human well-being, resource flows, and biodiversity (Strayer 2010; Lockwood et al. 2013).

The dispersal of species and the flow of freshwater, nutrients, and sediments can be encumbered by dams, levees, and other infrastructure barriers, such as roads and railways (Thieme et al. 2023). These barriers disconnect surface water from floodplains and associated groundwater. The construction of many more hydropower dams, as is proposed to reach net-zero emission targets by 2050 (IHA 2022), may, even if done as sustainably as possible, have adverse impacts on freshwater biodiversity. Conversely, sometimes infrastructure can have unintended benefits such as where barriers have created refuges from invasive species (e.g., Hrodey et al. 2021) or from rising water temperatures (e.g., Weber et al. 2017). Future-proofing strategies that consider the implications for biodiversity as well as for all relevant resource users (e.g., beyond just energy) can help ensure that proper accounting feeds into decision making for these large-scale projects (Jones and Bull 2020; Cid et al. 2022).

Future-proofing strategies for freshwater biodiversity

Given the inherent value and importance of freshwater biodiversity and the uncertainty of future conditions, implementation of the Emergency Recovery Plan needs to be resilient in the face of (1) likely future conditions, (2) unlikely but possible future conditions, and (3) unanticipated future conditions. Designing governance, management, and monitoring processes to inform ongoing adaptive management is a constant process of learning, with data and perspectives feeding into nimble management planning and delivery (e.g., Lynch et al. 2022). Looking to the past to determine what "should be" or what might be ecologically "optimal" is no longer the only option. Instead, future-proofing necessitates establishing new core values on what will be desirable to conserve (Domisch et al. 2019; Langhans et al. 2019; Matthews 2022; Vijay et al. 2022). These decisions can lean on scientific estimates of uncertainty in conjunction with other value and knowledge systems (e.g., traditional knowledge, aesthetics, and equity) to determine a range of possible futures and take actions that steer toward those that are preferred (Kellert 1996). In addition to strengthening collaborative and co-production practices, framing strategies at multiple spatial scales will be needed because ecological values are more likely to be protected at landscape rather than local scales (e.g., conservation of particular species or wetland types; Finlayson et al. 2017). For example, protected area network design can be adapted (e.g., shifting from terrestrial-based models) to account for processes and scales that are unique to freshwater and account for aquatic species migration patterns in response to climate change (Higgins et al. 2021). Indigenous and local community rights can be more prominently recognized, respected, and included in planning and management interventions (e.g., co-management with local communities) to help secure the protection of cultural values of freshwater ecosystems (Douglas et al. 2019; also see Boxes 1 and 2).

Future-proofing strategies will look beyond ideological but outdated approaches, such as eradication of all nonnative species and removal of all human infrastructure (see Britton et al. 2023; Theime et al. 2023). These approaches are often impossible and also, in particular situations, unnecessary as both nonnative species and artificial habitat have the potential to contribute to longer-term and larger-scale needs (e.g., shading; Capon and Palmer 2018). Rather, future-proofing strategies will build upon the strong foundation of existing successful management practices such as transboundary and multi-partner collaborations, management, and regulation; generation and implementation of innovative technologies and practices; and prioritization and optimization of conservation and infrastructure planning with a forward-looking lens (Fig. 1, Table 1). Future-proofing does not supplant ecological paradigms or management programs; it enhances them and makes them more nimble in their ability to adjust to future conditions by explicitly considering future uncertainty and plausible trajectories in planning processes.

Future-proofing the Emergency Recovery Plan will depend on credible, relevant, and legitimate science to support transformative change, as well as the uptake of science in policy and management. It will also depend on behavior and attitude changes for freshwater resource users and society as a whole (Loorbach and Oxenaar 2018; Birnie-Gauvin et al. 2023). Such fundamental changes require transformations initiated top-down (e.g., related to policies) but will fail without bottom-up, multi-disciplinary transitions (e.g., adoption of new technologies, practices, or capacities). For example, the latest National Policy Statement for Freshwater Management in New Zealand created and implemented a hierarchy of obligations based on opportunities for public engagement, stating that the health and well-being of the water body must be considered first, before human health, and then economic benefits (Table 1; New Zealand Government 2020). We recognize this ecocentric strategy may not be possible in all countries, but it highlights that integrated approaches are likely to be the most successful because they can optimize across multiple objectives and streamline implementation processes.

Future-proofing the Emergency Recovery Plan will also depend on quantifying, communicating, and leveraging the uncertainties in our scientific knowledge for the purpose of making better decisions. While acknowledging the importance of uncertainty in decision making for ecological systems feels relatively new, decision making under uncertainty has a long history and is well developed and used in business management (Sharma et al. 2020), legal systems (Kaye et al. 2020), the insurance industry (Daykin and Hey 1990), water management (Höllermann and Evers 2019), and for making personal decisions such as health care, parenting, and now even travel planning (Williams et al. 2022). However, the current causes of transformation are generally unprecedented and exceed historical ranges of variability (Thompson et al. 2021). Methods for acknowledging and incorporating uncertainty include development of scenarios (e.g., IPCC 2022*b*, and common financial planning advice), exploring and comparing distributions (e.g., Weitkamp et al. 2015), as well as evaluating model sensitivity (e.g., McElhany et al. 2010) and applying multiple models (Schuwirth et al. 2019). Facing and quantifying uncertainty, to the degree possible, is the first and essential step of decision making under most realistic situations. In every case, uncertainty, in and of itself, is information. Uncertainty is not an excuse for inaction but a call to action, including filling information gaps, systematically evaluating possibilities, and communicating probabilistically (Steel et al. 2009).

Human activities transform freshwater for water provision and related socio-economic benefits, often at the cost of degrading and impairing ecosystems and biodiversity. This water-socio-ecological nexus is multifaceted and complex (Vollmer et al. 2018). Ignoring risks of extreme events, unlikely but possible outcomes, or likely new conditions and interactions may yield poor and unexpected results. Downscaling ideas, tools, and processes involved in the management and conservation of freshwater ecosystems would be most effective by taking into consideration local conditions and traditional local knowledge (i.e., "think global, act local"; Cradock-Henry and Frame 2021; Twardek et al. 2021). For example, a focus on culturally significant fisheries can be key to uniting indigenous and non-indigenous peoples in conserving freshwater ecosystems (Noble et al. 2016).

However, it is important to note that just a local lens will not suffice to address many, if not most, current environmental issues (e.g., invasive species; Strayer 2022). In these instances, planning and management interventions can benefit from integrated approaches that recognize multiple, and usually conflicting, dimensions of freshwater (Douglas et al. 2019). To effectively future-proof the Emergency Recovery Plan, such holistic approaches will generally need to consider the watershed scale for the design of management strategies, incorporate hydro-socio-ecological dimensions, account for political and economic context, be inclusive, and capture cultural relationships, values, rights, and interests from multiple partners, collaborators, and societal groups (Fig. 1).

A future-proofed emergency recovery plan

Resolving the freshwater biodiversity crisis is an immediate need. Effective implementation of the Emergency Recovery Plan can help "bend the curve of global freshwater biodiversity loss" because drivers of change and actions we take now have implications for the future (e.g., Ripple et al. 2022). In the last decade, scientists have developed and provided cross-sectoral tools that can be applied to catchments and effectively capture complex hydro-ecological connections but also cultural relationships, values, rights, and interests (Vörösmarty et al. 2010; Vollmer et al. 2018; Douglas et al. 2019; Shaad and Alt 2020). The use of best available science and other knowledge systems using evidence-based processes can set freshwater protection goals, contribute to transition governance and improve policies, build capacity for monitoring and management, and support integrative strategies underpinning the Emergency Recovery Plan. Ensuring that response options within the Emergency Recovery Plan are future-proofed (which, in itself, requires perpetual revisiting in an adaptive management context) will provide decision makers with science-informed choices in the face of uncertainty (Table 1). We are at an inflection point for global freshwater biodiversity loss; we can learn from defeats and successes to ensure that freshwater biodiversity can contribute to a sustainable future (Fig. 1).

Acknowledgements

We thank Kate Malpeli, U.S. Geological Survey (USGS), for assistance with the figure and the other special section lead authors (Angela Arthington, Steve Ormerod, Morgan Piczak, Denielle Perry, Robert Britton, Eleri Pritchard, and Michele Thieme) for insightful contributions to this manuscript. We thank Sui Phang (The Nature Conservancy) for conducting an internal review of this manuscript for USGS and the journal reviewers and editors for helping further improve this manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Some authors are members of the international InFish Research Network (https://infish.org/). This manuscript contributes to the Alliance for Freshwater Life's vision to understand, value, and safeguard freshwater biodiversity (https://allianceforfreshwaterlife.org/).

Article information

History dates

Received: 9 November 2022
Accepted: 1 June 2023
Accepted manuscript online: 19 June 2023
Version of record online: 29 August 2023

Notes

This article is part of a special issue entitled "Recovery Plan for Freshwater Biodiversity".

Copyright

Data availability

Not applicable.

Author information

Author ORCIDs

Abigail J. Lynch https://orcid.org/0000-0001-8449-8392
Amanda A. Hyman https://orcid.org/0000-0002-3317-4774
Steven J. Cooke https://orcid.org/0000-0002-5407-0659
Samantha J. Capon https://orcid.org/0000-0002-1975-553X
Paul A. Franklin https://orcid.org/0000-0002-7800-7259
Sonja C. Jähnig https://orcid.org/0000-0002-6349-9561
Matthew McCartney https://orcid.org/0000-0001-6342-2815
Nguyễn Phú Hòa https://orcid.org/0000-0002-1050-7994
Margaret Awuor Owuor https://orcid.org/0000-0002-6734-7055
Jamie Pittock https://orcid.org/0000-0001-6293-996X
Michael J. Samways https://orcid.org/0000-0003-4237-6025
Luiz G. M. Silva https://orcid.org/0000-0002-2329-5601
E. Ashley Steel https://orcid.org/0000-0001-5091-276X
David Tickner https://orcid.org/0000-0001-5928-0869

Author notes

SJ Cooke is a member of the editorial advisory board of *Environmental Reviews*. The other authors declare no other conflicts of interests.

Author contributions

Conceptualization: AJL, SJ Cooke, DT
Project administration: AJL
Visualization: AJL, AAH, DT
Writing – original draft: AJL, AAH, SJ Cooke, SJ Capon, PAF, SCJ, MM, NPH, MAO, JP, MJS, LGMS, EAS, DT
Writing – review & editing: AJL, AAH, SJ Cooke, SJ Capon, PAF, SCJ, MM, NPH, MAO, JP, MJS, LGMS, EAS, DT

Competing interests

The authors declare no competing interests.

Funding information

SC Jähnig acknowledges funding by the Leibniz Competition Project: Freshwater Megafauna Futures. The other authors declare no specific funding for this work.

References

Allan, J.D., Abell, R., Hogan, Z., Revenga, C., Taylor, B.W., Welcomme, R.L., and Winemiller, K. 2005. Overfishing of inland waters. Bioscience, **55**(12): 1041–1051. doi:10.1641/0006-3568(2005)055[1041:OOIW]2.0.CO;2.

Arthington, A.H. 2021. Grand challenges to support the freshwater biodiversity Emergency Recovery Plan. Front. Environ. Sci. **9**(May): 1–6. doi:10.3389/fenvs.2021.664313.

Arthington, A.H., Tickner, D., McClain, M.E., Acreman, M.C., Anderson, E.P., Babu, S. et al. in press. Accelerating environmental flows implementation to bend the curve of global freshwater biodiversity loss. Environ. Rev.

Barnett, J., and O'Neill, S. 2010. Maladaptation. Global Environ. Change, **20**(2): 211–213. doi:10.1016/j.gloenvcha.2009.11.004.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., et al. 2010. Process-based principles for restoring river ecosystems. Bioscience, **60**(3): 209–222. doi:10.1525/bio.2010.60.3.7.

Bieroza, M.Z., Bol, R., and Glendell, M. 2021. What is the deal with the Green Deal: will the new strategy help to improve European freshwater quality beyond the Water Framework Directive? Sci. Total Environ. **791**: 148080. doi:10.1016/j.scitotenv.2021.148080. PMID: 34126496.

Birnie-Gauvin, K., Lynch, A.J., Franklin, P.A., Tickner, D., Reid, A.J., Landsman, S.J., et al. 2023. The RACE for freshwater biodiversity : essential actions to create the social context for meaningful conservation. **5**(February): 1–18. doi:10.1111/csp2.12911.

Britton, J.R., Lynch, A.J., Bardal, H., Bradbeer, S.J., Coetzee, J.A., Coughlan, N.E. et al. in press. Preventing and controlling nonnative species invasions to bend the curve of global freshwater biodiversity loss. Environ. Rev. **31**(2): 310–326. doi:10.1139/er-2022-0103.

Candler, C., Olson, R., and DeRoy, S.,Cooperation, F.G.R., Athabasca Chipewyan First Nation (ACFN), and M.C.F.N. 2010. As long as the rivers flow: Athabasca River knowledge, use and change—MCFN Community Report(16 August 2010): 271. Available from https://ww w.ceaa.gc.ca/050/documents/p65505/56876E.pdf [accessed 10 March 2023].

Capon, S., and Palmer, G. 2018. Turning over a new leaf: the role of novel riparian ecosystems in catchment management. Solutions, **9**(3). Available from https://thesolutionsjournal.com/2018/07/03/turning-new-leaf-role-novel-riparian-ecosystems-catchment-management/. PMID: 29938120 [accessed 11 August 2022].

Chapra, S.C., Boehlert, B., Fant, C., Bierman, V.J., Henderson, J., Mills, D., et al. 2017. Climate change impacts on harmful algal blooms in U.S. freshwaters: a screening-level assessment. Environ. Sci. Technol. **51**(16): 8933–8943. doi:10.1021/acs.est.7b01498. PMID: 28650153.

Chucholl, C., and Wendler, F. 2017. Positive selection of beautiful invaders : long-term persistence and bio-invasion risk of freshwater crayfish in the pet trade. Biol. Invasions, **19**(1): 197–208. doi:10.1007/s10530-016-1272-5.

Cid, N., Erős, T., Heino, J., Singer, G., Jähnig, S.C., Cañedo-Argüelles, M., et al. 2022. From meta-system theory to the sustainable management of rivers in the Anthropocene. Front. Ecol. Environ. **20**(1): 49–57. doi:10.1002/fee.2417. PMID: 35873359.

COFI. 2022. Mainstreaming biodiversity in fisheries and aquaculture. Committee on Fisheries, Rome, Italy. Available from https://www.fao.org/3/nj466en/nj466en.pdf [accessed 1 September 2022].

Collier, K.J., Baker, C., David, B.O., Górski, K., and Pingram, M.A. 2019. Linking ecological science with management outcomes on New Zealand' longest river. River Res. Appl. **35**(5): 476–488. doi:10.1002/rra.3181.

Collier, K.J., Watene-Rawiri, E.M., and McCraw, J.D. 2010. Geography and history. *In* The waters of the Waikato: ecology of New Zealand's longest river. *Edited by* K.J. Collier, D.P. Hamilton, W.N. Vant and C. Howard-Williams. University of Waikato, Hamilton, New Zealand. pp. 1–12. Available from www.ew.govt.nz/publications [accessed 11 August 2022].

Comte, L., and Grenouillet, G. 2013. Do stream fish track climate change? Assessing distribution shifts in recent decades. Ecography (Cop.), **36**(11): 1236–1246. doi:10.1111/j.1600-0587.2013.00282.x.

Cook, S., van Roon, M., Ehrenfried, L., LaGro, J., and Yu, Q. 2019. Chapter 27—WSUD "Best in Class"—case studies from Australia, New Zealand, United States, Europe, and Asia. *Edited by* A.K. Sharma and T. Gardner. Woodhead Publishing. pp. 561–585. doi:10.1016/B978-0-12-812843-5.00027-7.

Cooke, S.J., Piczak, M.L., Nyboer, E.A., Michalski, F., Bennett, A., Koning, A.A. et al. in press. Managing exploitation of freshwater species and aggregates to protect and restore freshwater biodiversity. Environ. Rev.

Cracknell, J., Vrana, M., and Mason, M. 2016. Environmental funding by European foundations volume 5. Brussels, Belgium. Available from https://www.efc.be/uploads/2021/04/Environmental-Funding-by-European-Foundations-vol.5.pdf [accessed 19 September 2022].

Cradock-Henry, N.A., and Frame, B. 2021. Balancing scales: enhancing local applications of adaptation pathways. Environ. Sci. Policy, **121**(March): 42–48. doi:10.1016/j.envsci.2021.04.001.

Craig, L.S., Olden, J.D., Arthington, A.H., Entrekin, S., Hawkins, C.P., Kelly, J.J., et al. 2017. Meeting the challenge of interacting threats in freshwater ecosystems: a call to scientists and managers. Elementa, **5**(1): 1–15. doi:10.1525/elementa.256.

Crausbay, S.D., Chaffin, B.C., Clifford, K.R., Cravens, A.E., Gross, J.E., Knapp, C.N., et al. 2022. A science agenda to support natural resource management decisions in an era of ecological transformation. Bioscience, **72**(1): 71–90. doi:10.1093/biosci/biab102.

Crossman, J., Futter, M.N., Oni, S.K., Whitehead, P.G., Jin, L., Butterfield, D., et al. 2013. Impacts of climate change on hydrology and water quality: future proofing management strategies in the Lake Simcoe watershed, Canada. J. Great Lakes Res. **39**(1): 19–32. doi:10.1016/j.jglr.2012.11.003.

Daly, H.E., and Farley, J.(*Editors*). 2010. Ecological economics. 2nd ed. Island Press, Washington, DC. Available from https://islandpress.org/books/ecological-economics-second-edition [accessed 24 February 2023].

Darwall, W., Smith, K., Allen, D., Holland, R., Harrison, I., and Brooks, E.(*Editors*). 2011. The diversity of life in African freshwaters: underwater, under threat—an analysis of the status and distribution of freshwater species throughout mainland Africa. IUCN (International Union for Conservation of Nature), Cambridge, UK, and Gland, Switzerland. Available from https://portals.iucn.org/library/sites/library/files/documents/RL-6-001.pdf [accessed 3 February 2022].

Daykin, C.D., and Hey, G.B. 1990. Managing uncertainty in a general insurance company. J. Inst. Actuaries, **117**(2): 173–277. Available from https://www.jstor.org/stable/pdf/41140973.pdf?refreqid=excelsior%3Aebbdd319c9a0439e5007cabab69c7c5e&ab_segments=&origin=&acceptTC=1. doi:10.1017/S0020268100043109 [accessed 14 September 2022].

Di Marco, M., Chapman, S., Althor, G., Kearney, S., Besancon, C., Butt, N., et al. 2017. Changing trends and persisting biases in three decades of conservation science. Global Ecol. Conserv. **10**: 32–42. doi:10.1016/j.gecco.2017.01.008.

Domisch, S., Kakouei, K., Martínez-López, J., Bagstad, K.J., Magrach, A., Balbi, S., et al. 2019. Social equity shapes zone-selection: balancing aquatic biodiversity conservation and ecosystem services delivery in the transboundary Danube River Basin. Sci. Total Environ. **656**: 797–807. doi:10.1016/j.scitotenv.2018.11.348. PMID: 30530149.

Douglas, M.M., Jackson, S., Canham, C.A., Laborde, S., Beesley, L., Kennard, M.J., et al. 2019. Conceptualizing hydro-socio-ecological relationships to enable more integrated and inclusive water allocation planning. One Earth, **1**(3): 361–373. doi:10.1016/j.oneear.2019.10.021.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I.I., Knowler, D.J., Leveque, C., et al. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. **81**(2): 163–182. doi:10.1017/s1464793105006950.

EEA. 2020. Floodplains: a natural system to preserve and restore. *In* EEA Report No. 24/2020. Copenhagen, Denmark. Available from https://www.eea.europa.eu/publications/floodplains-a-natural-system-to-preserve-and-restore [accessed 11 August 2022].

Emde, S., Rueckert, S., Palm, H.W., and Klimpel, S. 2012. Invasive Ponto-Caspian amphipods and fish increase the distribution range of the Acanthocephalan *Pomphorhynchus tereticollis* in the River Rhine. PLoS ONE, **7**(12). doi:10.1371/journal.pone.0053218. PMID: 23300895.

FAO. 2022. The state of the world's land and water resources for food and agriculture 2021—systems at breaking point. Main Report. Rome, Italy. doi:10.4060/cb9910en.

Feio, M.J., Hughes, R.M., Serra, S.R.Q., Nichols, S.J., Kefford, B.J., Lintermans, M., et al. 2022. Fish and macroinvertebrate assemblages reveal extensive degradation of the world's rivers. Global Change Biol. **29**(October): 355–374. doi:10.1111/gcb.16439.

Finlayson, C.M., Capon, S.J., Rissik, D., Pittock, J., Fisk, G., Davidson, N.C., et al. 2017. Policy considerations for managing wetlands under a changing climate. Mar. Freshwater Res. **68**(10): 1803–1815. doi:10.1071/MF16244.

Frietsch, M., Loos, J., Löhr, K., Sieber, S., and Fischer, J. 2023. Future-proofing ecosystem restoration through enhancing adaptive capacity. Commun. Biol. **6**(1): 377. doi:10.1038/s42003-023-04736-y. PMID: 37029278.

Gilfillan, D., and Pittock, J. 2022. Pumped storage hydropower for sustainable and low-carbon electricity grids in Pacific Rim economies. Energies, **15**: 3139. doi:10.3390/en15093139.

Gillespie, N., Unthank, A., Anderson, P., Campbell, L., Gubernick, R., Weinhold, M., et al. 2014. Flood effects on road–stream crossing infrastructure: economic and ecological benefits of stream simulation designs. Fisheries, **39**(2): 62–76. doi:10.1080/03632415.2013.874527.

Goulson, D. 2019. The insect apocalypse, and why it matters. Curr. Biol. **29**(19): R967–R971. doi:10.1016/j.cub.2019.06.069. PMID: 31593678.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., et al. 2019. Mapping the world's free-flowing rivers. Nature, **569**(7755): 215–221. doi:10.1038/s41586-019-1111-9. PMID: 31068722.

Gupta, J., and Schmeier, S. 2020. Future proofing the principle of no significant harm. Int. Environ. Agreements Polit. Law Econ. **20**(4): 731–747. doi:10.1007/s10784-020-09515-2.

Halleux, V. 2023. Urban wastewater treatment: updating EU rules. Available from https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2023)739370 [accessed 6 March 2023].

Hanchet, S.M. 1990. Effect of land use on the distribution and abundance of native fish in tributaries of the Waikato River in the Hakarimata Range, North Island, New Zealand. N. Z. J. Mar. Freshwater Res. **24**(2): 159–171. doi:10.1080/00288330.1990.9516411.

Harmsworth, G., Awatere, S., and Robb, M. 2016. Indigenous Maori values and perspectives to inform freshwater management in Aotearoa-New Zealand. Ecol. Soc. **21**(4): art9. doi:10.5751/ES-08804-210409.

Harper, M., Mejbel, H.S., Longert, D., Abell, R., Beard, T.D., Bennett, J.R., et al. 2021. Twenty-five essential research questions to inform the protection and restoration of freshwater biodiversity. Aquat. Conserv. Mar. Freshwater Ecosyst. **31**(9): 2632–2653. doi:10.1002/aqc.3634.

Heino, J., Culp, J.M., Erkinaro, J., Goedkoop, W., Lento, J., Rühland, K.M., and Smol, J.P. 2020. Abruptly and irreversibly changing Arctic freshwaters urgently require standardized monitoring. J. Appl. Ecol. **57**(7): 1192–1198. doi:10.1111/1365-2664.13645.

Hermoso, V. 2017. Freshwater ecosystems could become the biggest losers of the Paris Agreement. Global Change Biol. **23**(9): 3433–3436. doi:10.1111/gcb.13655. PMID: 28181724.

Hermoso, V., and Kennard, M.J. 2012. Uncertainty in coarse conservation assessments hinders the efficient achievement of conservation goals. Biol. Conserv. **147**(1): 52–59. doi:10.1016/j.biocon.2012.01.020.

Hieronymus, M., and Kalén, O. 2022. Should Swedish sea level planners worry more about mean sea level rise or sea level extremes? Ambio, **51**: 2325–2332. doi:10.1007/s13280-022-01748-6. PMID: 35670900.

Higgins, J., Zablocki, J., Newsock, A., Krolopp, A., Tabas, P., and Salama, M. 2021. Durable freshwater protection: a framework for establishing and maintaining long-term protection for freshwater ecosystems and the values they sustain. Sustainability, **13**(4): 1–17. doi:10.3390/su13041950.

Höllermann, B., and Evers, M. 2019. Coping with uncertainty in water management: qualitative system analysis as a vehicle to visualize the plurality of practitioners' uncertainty handling routines. J. Environ. Manage. **235**(January): 213–223. doi:10.1016/j.jenvman.2019.01.034. PMID: 30682674.

Hrodey, P.J., Lewandoski, S.A., Sullivan, W.P., Barber, J.M., Mann, K.A., Paudel, B., and Symbal, M.J. 2021. Evolution of the sea lamprey control barrier program: the importance of lowermost barriers. J. Great Lakes Res. **47**: S285–S296. doi:10.1016/j.jglr.2021.10.006.

IHA. 2022. Hydropower status report 2022. London, UK. Available from https://assets-global.website-files.com/5f749e4b9399c80b5e421384/62c402eb2af8db8431332d62_IHA-2022-Hydropower-Status-Report.pdf [accessed 5 July 2022].

IPBES. 2019. Global assessment report on biodiversity and ecosystem services. Chapter 2.2 status and trends—nature. *In* Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Available from https://www.ipbes.net/global-assessment%0Ahttps://ipbes.net/global-assessment [accessed 30 June 2022].

IPCC. 2022a. Summary for policymakers. *In* Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Edited by* H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegr, M. Craig, S. Langsdorf, S. Löschke, V. Möller, and A. Okem. Cambridge University Press, Cambridge, UK, and New York, NY, USA. pp. 3–33. doi:10.1017/9781009325844.001.

IPCC. 2022b. Climate Change 2022: impacts, adaptation, and vulnerability. *In* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Edited b y* H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama. Cambridge University Press, Cambridge, UK. Available from https://www.ipcc.ch/report/ar6/wg2/about/how-to-cite-this-report/ [accessed 30 August 2022].

Jähnig, S.C., Carolli, M., Dehnhardt, A., Jardine, T., Podschun, S., Pusch, M., et al. 2022. Ecosystem services of river systems—irreplaceable, undervalued, and at risk. *In* Encyclopedia of inland waters. 2nd ed. *Edited by* T. Mehner. Elsevier Inc., Oxford. doi:10.1016/b978-0-12-819166-8.00129-8.

Jerde, C.L., Mahon, A.R., Chadderton, W.L., and Lodge, D.M. 2011. "Sight-unseen" detection of rare aquatic species using environmental DNA. Conserv. Lett. **4**(2): 150–157. doi:10.1111/j.1755-263X.2010.00158.x.

Jones, I.L., and Bull, J.W. 2020. Major dams and the challenge of achieving "No Net Loss" of biodiversity in the tropics. Sustainable Dev. **28**(2): 435–443. doi:10.1002/sd.1997.

Kaye, P.H., Smith, A.D., Strudwick, M.J., White, M., Bird, C.E.L., Aggarwal, G., et al. 2020. Managing uncertainty: principles for improved decision making. Br. Actuarial J. **25**: 1–51. doi:10.1017/S135732172000015X.

Kellert, S.R. 1996. The value of life: biological diversity and human society. Island Press, Washington, DC. doi:10.1177/027046769601600415.

Kietzka, G.J., Pryke, J.S., and Samways, M.J. 2015. Landscape ecological networks are successful in supporting a diverse dragonfly assemblage. Insect Conserv. Diversity, **8**(3): 229–237. John Wiley & Sons, Ltd. doi:10.1111/icad.12099.

Kietzka, G.J., Pryke, J.S., Gaigher, R., and Samways, M.J. 2019. Applying the umbrella index across aquatic insect taxon sets for freshwater assessment. Ecol. Indic. **107**(March): 105655. doi:10.1016/j.ecolind.2019.105655.

Kietzka, G.J., Pryke, J.S., Gaigher, R., and Samways, M.J. 2021. Webs of well-designed conservation corridors maintain river ecosystem integrity and biodiversity in plantation mosaics. Biol. Conserv. **254**: 108965. doi:10.1016/j.biocon.2021.108965.

Lacerda Macêdo, R., Clara Sampaio Franco, A., Russo, P., Collart, T., Mammola, S., Jeppesen, E., et al. 2021. Climate and landscape changes enhance the global spread of a bloom-forming dinoflagellate related to fish kills and water quality deterioration. Ecol. Indic. **133**(September): 108408. doi:10.1016/j.ecolind.2021.108408.

Langhans, S.D., Jähnig, S.C., and Schallenberg, M. 2019. On the use of multicriteria decision analysis to formally integrate community values into ecosystem-based freshwater management. River Res. Appl. **35**(10): 1666–1676. doi:10.1002/rra.3388.

Lim, M. 2014. Is water different from biodiversity? Governance criteria for the effective management of transboundary resources. Rev. Eur. Comp. Int. Environ. Law, **23**(1): 96–110. John Wiley & Sons, Ltd. doi:10.1111/reel.12072.

Liu, H., Jia, Y., and Niu, C. 2017. "Sponge city" concept helps solve China's urban water problems. Environ. Earth Sci. **76**(14): 1–5. doi:10.1007/s12665-017-6652-3.

Lockwood, J.L., Hoopes, M.F., and Marchetti, M.P.(*Editors*). 2013. Invasion ecology. 2nd ed. Wiley-Blackwell, West Sussex, UK.

Loorbach, D., and Oxenaar, S. 2018. Counting on nature: transitions to a natural capital positive economy by creating an enabling environment for Natural Capital Approaches. Rotterdam, The Netherlands. doi:10.5422/fordham/9780823244881.003.0005.

Lott, M.J., Wright, B.R., Neaves, L.E., Frankham, G.J., Dennison, S., Eldridge, M.D.B., et al. 2022. Future-proofing the koala: synergising genomic and environmental data for effective species management. Mol. Ecol. **31**(11): 3035–3055. doi:10.1111/mec.16446. PMID: 35344635.

Loucks, D.P., and van Beek, E. 2016. Water resource systems planning and analysis—an Introduction to methods, models, and applications. *In* Advances in water resources.

Lynch, A.J., Cooke, S.J., Arthington, A.H., Baigun, C., Bossenbroek, L., Dickens, C., et al. 2023. People need freshwater life. WIREs Water, **10**(3): e1633. doi:10.1002/wat2.1633.

Lynch, A.J., Thompson, L.M., Morton, J.M., Beever, E.A., Clifford, M., Limpinsel, D., et al. 2022. RAD adaptive management for transforming ecosystems. Bioscience, **72**(1): 45–56. doi:10.1093/biosci/biab091.

Magness, D.R., Wagener, E., Yurcich, E., Mollnow, R., Granfors, D., and Wilkening, J.L. 2022. A multi-scale blueprint for building the decision context to implement climate change adaptation on national wildlife refuges in the United States. Earth, **3**(1): 136–156. doi:10.3390/earth3010011.

Manu, A. 2021. Dynamic future-proofing: integrating disruption in everyday business. Emerald Publishing Limited, Bingley, UK. Available from https://books.emeraldinsight.com/page/detail/dynamic-future-proofing/?k=9781800435278 [accessed 14 September 2022].

Marden, M. 2004. Future-proofing erosion-prone hill country against soil degradation and loss during large storm events: have past lessons been heeded? N. Z. J. For. **49**: 11–16.

Masood, T., McFarlane, D., Parlikad, A.K., Dora, J., Ellis, A., and Schooling, J. 2016. Towards the future-proofing of UK infrastructure. Infrastruct. Asset Manage. **3**(1): 28–41. doi:10.1680/jinam.15.00006 [accessed 14 September 2022].

Matthews, J.H. 2022. Climate change killed conservation: can we still protect ecosystems? Available from https://medium.com/@johoma/c limate-change-killed-conservation-can-we-still-protect-ecosystems-80144df200e4 [accessed 11 August 2022].

Mazor, T., Runting, R.K., Saunders, M.I., Huang, D., Friess, D.A., Nguyen, N.T.H., et al. 2021. Future-proofing conservation priorities for sea level rise in coastal urban ecosystems. Biol. Conserv. **260**(May): 109190. doi:10.1016/j.biocon.2021.109190.

McElhany, P., Steel, E.A., Avery, K., Yoder, N., Busack, C., and Thompson, B. 2010. Dealing with uncertainty in ecosystem models: lessons from a complex salmon model. Ecol. Appl. **20**(2): 465–482. doi:10.1890/08-0625.1.

Mendoza, S.J.E., Amaya, E.J.D., Terán, N.P., Ramos, M.A., Vargas, T.N., Cediel, F.M., et al. 2020. National policy for the integral management of biodiversity and its ecosystemic services. Available from https://www.cbd.int/doc/world/co/co-nbsap-v2-en.pdf [accessed 7 March 2023].

Mittermeier, R.A., Gil, P.R., Hoffman, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., et al. 2005. Hotspots revisited: Earth's biologically richest and most endangered terrestrial ecoregions. University of Chicago Press, Chicago, IL. Available from https://press.uchicago.edu/ucp/books/book/distributed/H/bo3707156.html [accessed 3 February 2022].

Montgomery, G.A., Dunn, R.R., Fox, R., Jongejans, E., Leather, S.R., Saunders, M.E., et al. 2020. Is the insect apocalypse upon us? How to find out. Biol. Conserv. **241**: 108327. doi:10.1016/j.biocon.2019.108327.

New Zealand Government. 2020. National policy statement for freshwater management 2020. Wellington, New Zealand.

Noble, M., Duncan, P., Perry, D., Prosper, K., Rose, D., Schnierer, S., et al. 2016. Culturally significant fisheries: keystones for management of freshwater social-ecological systems. Ecol. Soc. **21**(2): art22. doi:10.5751/ES-08353-210222.

O'Briain, R., Shephard, S., and Coghlan, B. 2017. River reaches with impaired riparian tree cover and channel morphology have reduced thermal resilience. Ecohydrology, **10**(8): 1–9. doi:10.1002/eco.1890.

Opperman, J.J., Carvallo, J.P., Kelman, R., Schmitt, R.J.P., Almeida, R., Chapin, E., et al. 2023. Balancing renewable energy and river resources by moving from individual assessments of hydropower projects to energy system planning. Front. Environ. Sci. **10**(January): 1–26. doi:10.3389/fenvs.2022.1036653.

Ormerod, S. et al. in press. Improving water quality. Environ. Rev

Parlee, B. 2011. Traditional knowledge overview for the Athabasca River watershed: contributed to the Athabasca Watershed Council State of the Watershed Phase 1 Report. Edmonton, AB. Available from www.specialplaces.ca [accessed 14 October 2022].

Paterson-Shallard, H., Blue, B., and Fisher, K. 2022. A change of plan: collaborative ambitions meet institutional realities for the Waikato River. N. Z. Geogr. **78**(1): 63–75. doi:10.1111/nzg.12326.

Phang, S.C., Cooperman, M., Lynch, A.J., Steel, E.A., Elliott, V., Murchie, K.J., et al. 2019. Fishing for conservation of freshwater tropical fishes in the Anthropocene. Aquat. Conserv. Mar. Freshwater Ecosyst. **29** 1039–1051. doi:10.1002/aqc.3080.

Piczak, M.L., Perry, D., Cooke, S.J., Harrison, I., Benitez, S., Koning, A. et al. 2023. Measures to safeguard and restore river connectivity. Environ. Rev. doi:10.1139/er-2023-0019.

Pingram, M.A., Collier, K.J., Williams, A.K., David, B.O., Garrett-Walker, J., Górski, K., et al. 2021. Surviving invasion: regaining native fish resilience following fish invasions in a modified floodplain landscape. Water Resour. Res. **57**(9): 1–22. doi:10.1029/2020WR029513.

Pryke, J.S., and Samways, M.J. 2012. Ecological networks act as extensions of protected areas for arthropod biodiversity conservation. J. Appl. Ecol. **49**(3): 591–600. doi:10.1111/j.1365-2664.2012.02142.x.

Rehman, O.U., Ryan, M.J., and Efatmaneshnik, M. 2017. Future proofing process. INCOSE Int. Symp. **27**(1): 921–934. doi:10.1002/j.2334-5837.2017.00403.x.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., et al. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. **94**: 849–873. doi:10.1111/brv.12480.

Ricciardi, A., and MacIsaac, H.J. 2000. Recent mass invasion of the North American Great Lakes by Ponto–Caspian species. Trends Ecol. Evol. **15**(2): 62–65. doi:10.1016/S0169-5347(99)01745-0.

Ripple, W.J., Wolf, C., Newsome, T.M., Gregg, J.W., Lenton, T.M., Palomo, I., et al. 2022. World scientists' warning of a climate emergency 2022. Bioscience, **72**(12): 1149–1155. doi:10.1093/biosci/biab079.

Samways, M.J. 2015. Future-proofing insect diversity. Curr. Opin. Insect Sci. **12**: 71–78. doi:10.1016/j.cois.2015.09.008.

Samways, M.J. 2020. Insect conservation: a global synthesis. CABI Publishing, Wallingford, UK. Available from https://www.cabi.org/bookshop/book/9781789241686/ [accessed 23 July 2022].

Samways, M.J., and Pryke, J.S. 2016. Large-scale ecological networks do work in an ecologically complex biodiversity hotspot. Ambio, **45**(2): 161–172. doi:10.1007/s13280-015-0697-x.

Schuwirth, N., Borgwardt, F., Domisch, S., Friedrichs, M., Kattwinkel, M., Kneis, D., et al. 2019. How to make ecological models useful for environmental management. Ecol. Model. **411**(September): 108784. doi:10.1016/j.ecolmodel.2019.108784.

Serra-Llobet, A., Jähnig, S.C., Geist, J., Kondolf, G.M., Damm, C., Scholz, M., et al. 2022. Restoring rivers and floodplains for habitat and flood risk reduction: experiences in multi-benefit floodplain management from California and Germany. Front. Environ. Sci. **9**(March): 1–24. doi:10.3389/fenvs.2021.778568.

Shaad, K., and Alt, H. 2020. An open source toolbox for integrating freshwater social–ecological indicators in basin management. J. Open Res. Softw. **8**(1): 1–6. doi:10.5334/JORS.291.

Sharma, P., Leung, T.Y., Kingshott, R.P.J., Davcik, N.S., and Cardinali, S. 2020. Managing uncertainty during a global pandemic: an international business perspective. J. Bus. Res. **116**(January): 118–192.

Silva, R.V., Jiménez, J.R., Agrela, F., and de Brito, J. 2019. Real-scale applications of recycled aggregate concrete. *In* New trends in eco-efficient and recycled concrete. *Edited by* J.D. Brito and R.C. Agrela. Woodhead Publishing. pp. 573–589. doi:10.1016/B978-0-08-102480-5.00021-X.

Simberloff, D. 2021. Maintenance management and eradication of established aquatic invaders. Hydrobiologia, **848**(9): 2399–2420. doi:10.1007/s10750-020-04352-5.

Speed, R., Li, Y., Tickner, D., Huang, H., Naiman, R., Cao, J., et al. 2016. River restoration: a strategic approach to planning and management. UNESCO, Paris, France. doi:10.1007/978-1-62703-595-8_4.

Steel, E.A., Beechie, T.J., Ruckelshaus, M.H., Fullerton, A.H., McElhany, P., and Roni, P. 2009. Mind the gap: uncertainty and model communication between managers and scientists.

Stoffels, R.J., Franklin, P.A., Fragaszy, S.R., Booker, D.J., Clapcott, J.E., Snelder, T.H., et al. 2021. Multiple framings of uncertainty shape adoption of reference states during reform of water policy. Environ. Sci. Policy, **124**(September 2020): 496–505. doi:10.1016/j.envsci.2021.07.026.

Strayer, D.L. 2010. Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshwater Biol. **55**(SUPPL. 1): 152–174. doi:10.1111/j.1365-2427.2009.02380.x.

Strayer, D.L. 2022. Think locally and act globally on invasive species. Nat. Areas J. **42**(2): 108. doi:10.3375/0885-8608-42.2.108.

Suárez, C.F., Paez-Vasquez, M., Trujillo, F., Usma, J.S., Thieme, M., Bassi, A.M., et al. 2021. How to protect free flowing rivers: the Bita River Ramsar site as an example of science and management tools working together. Sustainability, **13**(4): 1–16. doi:10.3390/su13041775.

Te Aho, L. 2010. Indigenous challenges to enhance freshwater governance and management in Aotearoa New Zealand—the Waikato River settlement. J. Water Law, **20**(5): 285–292. Available from https://waikato.researchgateway.ac.nz/bitstream/handle/10289/5705/INDIGENOUS CHALLENGES.pdf?sequence=1&isAllowed=y [accessed 15 March 2018].

Te Aho, L. 2019. Te Mana o te Wai: an indigenous perspective on rivers and river management. River Res. Appl. **35**(10): 1615–1621. doi:10.1002/rra.3365.

Thieme, M., Birnie-Gauvin, K., Opperman, J.J., Franklin, P.A., Richter, H., Baumgartner, L. et al. 2023. Measures to safeguard and restore river connectivity. Environ. Rev.doi:10.1139/er-2023-0019.

Thompson, L.M., Lynch, A.J., Beever, E.A., Engman, A.C., Falke, J.A., Jackson, S.T., et al. 2021. Responding to ecosystem transformation: resist, accept, or direct? Fisheries, **46**(1): 8–21. doi:10.1002/fsh.10506.

Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., et al. 2020. Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. Bioscience, **70**: 330–342. doi:10.1093/biosci/biaa002.

Tilman, D. 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proc. Natl. Acad. Sci. U.S.A. **96**(11): 5995–6000. doi:10.1073/pnas.96.11.5995.

Timpane-Padgham, B.L., Beechie, T., and Klinger, T. 2017. A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. PLoS ONE, **12**(3): 1–23. doi:10.1371/journal.pone.0173812.

TNC. 2022. Financing nature for water security: a how-to guide to develop watershed investment programs. Version 1. Arlington, VA. Available from https://www.nature.org/content/dam/tnc/nature/en/documents/Watershed-Investment-Programs_How-to-Guide.pdf [accessed 8 November 2022].

Tonkin, J.D., Poff, N.L., Bond, N.R., Horne, A., Merritt, D.M., Reynolds, L. V., et al. 2019. Prepare river ecosystems for an uncertain future. Nature, **570**: 301–303. doi:10.1038/d41586-019-01877-1.

Twardek, W.M., Nyboer, E.A., Tickner, D., O'Connor, C.M., Lapointe, N.W.R., Taylor, M.K., et al. 2021. Mobilizing practitioners to support the Emergency Recovery Plan for freshwater biodiversity. Conserv. Sci. Pract. **3**(8): 1–14. doi:10.1111/csp2.467.

UNEP. 2021. Future-proofing infrastructure to address the climate, biodiversity and pollution crises. United Nations Environment Programme (UNEP), Nairobi, Kenya. Available from http://www.un.org/Depts/Cartographic/english/htmain [accessed 10 May 2023].

Van Dijk, A.I.J.M., Evans, R., Hairsine, P., Khan, S., Nathan, R., Paydar, Z., et al. 2006. Risks to the shared water resources of the Murray–Darling Basin. MDBC Publication No. 22/06. Canberra, Australia. Available from https://publications.csiro.au/rpr/download?pid=procite:fa89ebbb-8274-415f-904c-f0809bfaa29e&dsid=DS1 [accessed 30 August 2022].

van Kerkhoff, L., Munera, C., Dudley, N., Guevara, O., Wyborn, C., Figueroa, C., et al. 2019. Towards future-oriented conservation: managing protected areas in an era of climate change. Ambio, **48**(7): 699–713. doi:10.1007/s13280-018-1121-0. PMID: 30448995.

Vijay, V., Fisher, J.R.B., and Armsworth, P.R. 2022. Co-benefits for terrestrial biodiversity and ecosystem services available from contrasting land protection policies in the contiguous United States. Conserv. Lett. **15**(February): 1–9. doi:10.1111/conl.12907.

Vollmer, D., Shaad, K., Souter, N.J., Farrell, T., Dudgeon, D., Sullivan, C.A., et al. 2018. Integrating the social, hydrological and ecological dimensions of freshwater health: the Freshwater Health Index. Sci. Total Environ. **627**: 304–313. doi:10.1016/j.scitotenv.2018.01.040.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., et al. 2010. Global threats to human water security and river biodiversity. Nature, **467**(7315): 555–561. doi:10.1038/nature09440.

Vos, M., Hering, D., Gessner, M.O., Leese, F., Schäfer, R.B., Tollrian, R., et al. 2023. The Asymmetric Response Concept explains ecological consequences of multiple stressor exposure and release. Sci. Total Environ. **872**(February): 162196. doi:10.1016/j.scitotenv.2023.162196.

Waikato Regional Council. 2020. Proposed Waikato Regional Plan Change 1—Waikato and Waipa River Catchments: Te Panonitanga 1 i te Mahere Ā-Rohe a Waikato e Marohitia Nei: Ngā Riu o Ngā Awa o Waikato me Waipā. Hamilton, New Zealand. Available from https://www.waikatoregion.govt.nz/assets/WRC/WRC-2019/Volume-2-Proposed-Waikato-Regional-Plan-Change-1-Decisions-version.pdf [accessed 11 August 2022].

Waikato River Authority. 2008. Restoring and protecting the health and wellbeing of the Waikato River: vision and strategy for the Waikato River. Prepared by the GEC. Waikato, Hamilton, New Zealand. Available from https://waikatoriver.org.nz/wp-content/uploads/2019/03/Vision-and-Strategy-Reprint-2019web.pdf [accessed 11 August 2022].

Waikato River Authority. 2021. Five Year Report, 2021. Ka maatakitaki iho au ki te riu o Waikato. Hamilton, New Zealand.

Wang, H., García Molinos, J., Heino, J., Zhang, H., Zhang, P., and Xu, J. 2021. Eutrophication causes invertebrate biodiversity loss and decreases cross-taxon congruence across anthropogenically-disturbed lakes. Environ. Int. **153**: 106494. doi:10.1016/j.envint.2021.106494.

Weber, N., Bouwes, N., Pollock, M.M., Volk, C., Wheaton, J.M., Wathen, G., et al. 2017. Alteration of stream temperature by natural and artificial beaver dams. PLoS ONE, **12**(5): 1–23. doi:10.1371/journal.pone.0176313.

Weitkamp, L.A., Teel, D.J., Liermann, M., Hinton, S.A., Van Doornik, D.M., and Bentley, P.J. 2015. Stock-specific size and timing at ocean entry of Columbia River juvenile chinook salmon and steelhead: implications for early ocean growth. Mar. Coastal Fish. **7**: 370–392. doi:10.1080/19425120.2015.1047476.

Wentworth Group of Concerned Scientists. 2020. Assessment of river flows in the Murray–Darling Basin: observed versus expected flows under the Basin Plan 2012–2019. Sydney, Australia. Available from https://wentworthgroup.org/wp-content/uploads/2020/08/MDB-flows.pdf [accessed 30 August 2022].

Williams, A.M. Chen, J.L. Li, G. and Baláž, V. 2022. Risk, uncertainty and ambiguity amid Covid-19: A multi-national analysis of international travel intentions. Ann. Tour. Res. **92**: 103346. doi:10.1016/j.annals.2021.103346.

Winkler, K., Fuchs, R., Rounsevell, M., and Herold, M. 2021. Global land use changes are four times greater than previously estimated. Nat. Commun. **12**(1): 1–10. doi:10.1038/s41467-021-22702-2.

Wood, G., Marzinelli, E.M., Coleman, M.A., Campbell, A.H., Santini, N.S., Kajlich, L., et al. 2019. Restoring subtidal marine macrophytes in the Anthropocene: trajectories and future-proofing. Mar. Freshwater Res. **70**(7): 936–951. doi:10.1071/MF18226.

Worthington, T.A., van Soesbergen, A., Berkhuysen, A., Brink, K., Royte, J., Thieme, M., et al. 2022. Global swimways for the conservation of migratory freshwater fishes. Front. Ecol. Environ. **20**(10): 573–580. doi:10.1002/fee.2550.

Wu, Y., Zhang, G., Rousseau, A.N., Xu, Y.J., and Foulon, É. 2020. On how wetlands can provide flood resilience in a large river basin: a case study in Nenjiang River Basin, China. J. Hydrol. **587**(December 2019): 125012. doi:10.1016/j.jhydrol.2020.125012.

WWF. 2022. Living planet report 2022: building a nature-positive society. *In* A Banson production. *Edited by* R.E.A. Almond, M. Grooten, D.J. Bignoli and T. Petersen. World Wildlife Fund (WWF), Gland, Switzerland. Available from http://www.ecoguinea.org/papers-development.html [accessed 20 October 2022].