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OVERVIEW

People need freshwater biodiversity

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Abstract
Freshwater biodiversity, from fish to frogs and microbes to macrophytes, provides a vast array of services to people. Mounting concerns focus on the accelerating pace of biodiversity loss and declining ecological function within freshwater ecosystems that continue to threaten these natural benefits. Here, we catalog nine fundamental ecosystem services that the biotic components of indigenous freshwater biodiversity provide to people, organized into three categories: material (food; health and genetic resources; material goods), non-material (culture; education and science; recreation), and regulating (catchment integrity; climate regulation; water purification and nutrient cycling). If freshwater biodiversity is protected, conserved, and restored in an integrated manner, as well as more broadly appreciated by humanity, it will continue to contribute to human well-being and our sustainable future via this wide range of services and associated nature-based solutions to our sustainable future.

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KEYWORDS
ecosystem services, freshwater biodiversity, freshwater ecosystems, freshwater life

1 | AN OPEN POLICY WINDOW FOR BIODIVERSITY CONSERVATION

The moment is ripe for innovative thinking and political action for biodiversity conservation, protection, and sustainable management. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) released its Global Assessment report in 2019 (Brondízio et al., 2019), the United Nations Framework Convention on Climate Change Glasgow Climate Pact signed in 2021 included explicit mention of nature and ecosystem conservation and restoration (UNFCCC, 2021), and (as of 2022) leaders of 94 countries and regions have endorsed the Leaders Pledge for Nature (https://www.leaderspledgefornature.org/). Collectively, these efforts have enhanced public awareness and political salience of nature and biodiversity challenges (Ruckelshaus et al., 2020). This growing recognition is increasing the need to "mainstream" biodiversity considerations into regional, national, and international policies in diverse fields such as land and water management, development and trade, transportation, environmental assessment, and spatial planning (Albert et al., 2020; Whitehorn et al., 2019).

At the same time, scholarly innovations are advancing our understanding of biodiversity threats and possible policy tools for addressing them. The literature on ecosystem services, for example, has grown tremendously and provides policymakers with conceptual tools to understand and assess the social–economic benefits of biodiversity (e.g., Díaz et al., 2018; Evers et al., 2018; McKinley et al., 2019). New interdisciplinary work on nature-based solutions (NbS) similarly has significant political appeal based on the principles of working with nature and promises of green growth (Seddon et al., 2020). This surge in attention and innovation offers a policy window (Kingdon, 1993) at multiple political scales and across jurisdictions for meaningful action on biodiversity protection and enhancement. Research on policy windows suggests that they typically open during times of heightened urgency and attention but can be quick to close as public and political priorities shift (Birkmann et al., 2010; Rose et al., 2020; Young et al., 2021). Given that signatories to the UN Convention on Biological Diversity have largely failed to meet the Aichi targets for biodiversity conservation for the period 2010–2020, and that they will be committing to implement a Post-2020 Global Biodiversity Framework with new goals and targets (CBD, 2021), there is a narrow opportunity for political and policy change.

2 | A FOCUS ON FRESHWATER BIODIVERSITY

While these policy opportunities are available for biodiversity conservation in the broadest sense, they are especially critical for *freshwater* biodiversity. One-third of freshwater species are threatened with extinction according to the 2022 International Union for Conservation of Nature (IUCN) Red List; this includes 58.5% of freshwater turtles, 21.7% freshwater fishes, 30% freshwater crayfish, 37.3% of freshwater mammals, and 29.9% of amphibians, though these figures may well be higher because this analysis does not account for data-deficient species which could, in fact, be threatened (IUCN, 2022). Globally, over a third of inland wetlands have experienced declines from 1970 to 2015, a rate three times that of forest decline (Convention on Wetlands, 2021; Darrah et al., 2019). And, only one-third of large rivers remain free-flowing from source to sea (Grill et al., 2019). The threats and driving forces for the ongoing loss of freshwater biodiversity are complex and interrelated and often distinct from those that affect terrestrial biodiversity (Bernhardt et al., 2022). Persistent threats to freshwater biodiversity include habitat loss and degradation, pollution, river fragmentation, flow modification, overexploitation, invasive species, and several emerging threats, such as changing climates, freshwater salinization, riverine aggregate mining, microplastic pollution, and pharmaceutical use, augment these existing threats (Dudgeon, 2019; Koehnken et al., 2020; Reid et al., 2019; Strayer & Dudgeon, 2010). Results of these changes have been documented in an 84% decline in the Living Planet Index for freshwater vertebrate populations between 1970 and 2016, a rate twice that of biodiversity loss in terrestrial and marine realms (WWF, 2020).

Biodiversity loss and declining ecological function within freshwater ecosystems compromise the natural benefits that support human life (Cardinale, 2011; Cardinale et al., 2012). Substantial threats to freshwater species may also put the most vulnerable human populations, who are likely to be highly dependent on freshwater biodiversity, at risk. As one telling example, Darwall et al. (2011) showed that the areas of greatest freshwater biodiversity richness in continental Africa also tend to be the areas where the human populations show highest levels of rural poverty, hence they are likely to be most directly dependent on the ecosystem services supplied by this biodiversity (Sanon et al., 2021). This important association between high freshwater biodiversity and the most vulnerable human populations has been echoed in global analyses of connections between catchment condition and human well-being (Fisher et al., 2019; Herrera et al., 2017). Disentangling these interdependencies is beyond the scope of this exercise. However, it is important to highlight that these relationships are at risk of collapse; because these same regions with vulnerable human populations are also where large numbers of freshwater species are already threatened with extinction (Garcia-Moreno et al., 2014). Consequently, though freshwater ecosystems are not well represented in the United Nations' Sustainable Development Goals (SDGs), they can contribute substantially to achieving them, particularly in these vulnerable regions (Lynch et al., 2017, 2020).

3 | A STRUCTURED DISTILLATION PROCESS

Here, our objective is to highlight a suite of critical ecosystem services depending on freshwater biodiversity (Jähnig et al., 2022; Lynch et al., 2021). We aim to provide insight into how important freshwater biodiversity is to people to reveal, in more detail, how the observed collapse in freshwater biodiversity impacts people, across all regions of the globe, rural–urban gradients, and the full socioeconomic spectrum, but perhaps most particularly indigenous and marginalized groups. Our overview of this topic provides expert-curated, high-level summaries for a broad audience. We seek to provide robust evidence that can be used by policymakers, science communicators, as well as by conservation and development communities, to advance sustainable management of freshwater resources, ensure functioning and resilient freshwater ecosystems, and to help "bend the curve of global freshwater biodiversity loss" (Tickner et al., 2020). The processes which we hope to inform, such as conservation, restoration, and water use practices, are likely to be most successful if tackled in an integrated, socio-ecological approach, considering whole systems, source-to-sea connections, as well as the environmental context in which freshwater organisms are embedded (Lapointe et al., 2014).

There are important challenges and prerequisites for framing this exercise. First, we bounded the scope to benefits that arise specifically from *freshwater* ecosystems (i.e., running and standing fresh waters, freshwater wetlands, and groundwaters) to maintain the focus on these vulnerable ecosystems which have historically received less attention from key audiences than terrestrial and marine systems (Abell & Harrison, 2020; Tickner et al., 2020). Second, we refined the focus to freshwater *biodiversity* because a substantial body of work (e.g., Díaz et al., 2018; Millennium Ecosystem Assessment (MEA), 2005) has already characterized freshwater ecosystem services which arise either directly from functions that depend on multiple processes or as emergent properties where abiotic and biotic components of freshwater ecosystems interact (Mayr, 1982). Third, we intentionally concentrated on *indigenous* organisms in natural systems; though non-indigenous species as well as artificial systems (e.g., aquaculture) are acknowledged to provide situationally specific human benefits (Naylor et al., 2021; Shackleton et al., 2019). Finally, we do recognize that some aspects of natural freshwater biodiversity carry risks to people (e.g., disease transmission, human–wildlife conflict) which may create an additional set of challenges for freshwater ecosystem management, but those dimensions lie beyond the scope of this overview. We recognize, nonetheless, that the maintenance and protection of ecosystem services that stem from native freshwater biodiversity require holistic, integrated approaches to the management of the physical and chemical environments in which organisms coexist in functioning communities.

With these guardrails, we coordinated a series of structured discussions among our diverse expert author team. These consisted of collaborative list-generating exercises between subteams across disciplines, career stage, and geography that were consolidated via group discussions to compile a consensus list of the nine most important goods and services that the *biotic* components of *indigenous* freshwater biodiversity provide (see Graphical Abstract; Table 1; Supplementary Materials). We included case studies from around the world to provide a diverse range of examples for each of these nine topics (Figure 1). We operated within the IPBES framework of material, non-material, and regulating Nature's Contributions to People (Díaz et al., 2018) to maintain familiar conventions for grouping, but note that this does not imply any scientific justification to the ordering (i.e., the categories are presented alphabetically and the services are presented alphabetically within the categories). Likewise, this, as well as any other ecosystem service framework, is an adjunct to the ethical arguments for biodiversity conservation and not a replacement for it (Reyers et al., 2012). Additionally, while the case studies and examples featured here do represent a wide range of freshwater biodiversity, we acknowledge that we are unable to feature all geographic regions with their distinct climates and complements of freshwater biodiversity.

4 | MATERIAL

4.1 | Food

Freshwater biodiversity provides substantial contributions to food production. Although aquatic foods are frequently categorized homogeneously as "seafood" or "fish" (Golden et al., 2021), they are diverse ranging from animals to plants and microorganisms. The FAO Fisheries and Aquaculture Statistics and Information Branch (ASFIS) database includes over 2500 different listings of freshwater food fish species alone (FAO, 2022). Rice *Oryza sativa* is a freshwater macrophyte and a global dietary staple, feeding 50% of the world's population (Thomaz, 2021). Inland capture fisheries for finfish, amphibians, reptiles, mollusks, crustaceans, and other aquatic invertebrates provide critical and diverse sources of protein, essential fatty acids, and micronutrients to many people around the world (FAO, 2016, 2019). More than 90% of inland capture fisheries are for human consumption (Welcomme et al., 2010), indicating that inland fisheries truly are food fisheries. With at least 43% of inland capture fisheries coming from 50 low-income food-deficit countries (Funge-Smith, 2018), inland capture fisheries are particularly important for food security. A study of the socio-economic value of freshwater species in the northern African region, for example, showed that, of the 128 freshwater fishes included in the study, at least 46% are of socio-economic value and utilized in northern Africa, and 77% are utilized in continental Africa; most of these species are used for food (Juffe-Bignoli & Darwall, 2012). However, almost 36% of the 59 species used in northern Africa are threatened with regional extinction (Juffe-Bignoli & Darwall, 2012).

Freshwater wetlands are frequently sourced to augment food requirements by hunting game such as geese, ducks, or crocodiles, and gathering aquatic plants. The Yala Wetland in Kenya, for instance, provides high-quality edible plants all year round, unlike the surrounding areas, and provides sustainable hunting opportunities for the swamp-dwelling antelope, the sitatunga *Tragelaphus spekii*. Aboriginals of eastern central Australia grind the nut-like sporocarps of the semi-aquatic fern *Marsilea drummondii* (nardoo) to make a watery gruel or thin cakes (Ens et al., 2017). In North America, wild rice (manoomin) has been a physical and spiritual sustenance to the Ojibwe people since settling in the Lake Superior region and continues to be a highly nutritious staple of Ojibwe diets today (Barton, 2018).

TABLE 1 A suite of critical ecosystem services dependent on freshwater biodiversity overlayed on the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) reporting categories of Nature's Contributions to People (descriptions modified from table S1 in Díaz et al., 2018)

Material	Food	Production/harvest of food/nutritional resources from wild, managed, or domesticated organisms. Includes a wide range of finfish, invertebrates, waterbirds, freshwater algae, and more. Extends beyond nutritional security support (and associated health and wellness benefits) to include livelihood support from those that are involved with production, harvest, processing, preparation or other aspects of freshwater food production systems.
Material	Material goods	Production of materials derived from organisms in cultivated or wild ecosystems, for construction, clothing, printing, and ornamental purposes. Live organisms being directly used for decoration (e.g., fish or turtles in households and public spaces, aquatic plants) and company (e.g., pets).
Material	Health and genetic resources	Production of materials derived from organisms used for medicinal, veterinary, and pharmacological (e.g., poisonous, psychoactive) purposes. Production of genes and genetic information used for plant and animal breeding and biotechnology.
Non-material	Recreation	Provision, by freshwater ecosystems, habitats, or organisms, of opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, tourism, and aesthetic enjoyment based on the close contact with nature (e.g., swimming, fishing, birdwatching, snorkeling).
Non-material	Culture	Water, freshwater ecosystems, habitats or organisms being the basis for religious, spiritual, and social-cohesion experiences. Provisioning of opportunities by nature for people to develop a sense of place, belonging, rootedness, or connectedness, associated and servings as basis for narratives, rituals, and celebrations provided by water, freshwater ecosystems, habitats, species, or organisms.
Non-material	Science and education	Provision, by freshwater ecosystems, habitats, or organisms, of opportunities for the development of the capabilities that allow humans to prosper through education, acquisition of knowledge and development of skills for well-being, information, and inspiration for art and technological design (e.g., biomimicry).
Regulating	Climate regulation	Climate regulation by ecosystems (including regulation of global warming). Positive or negative effects on emissions of greenhouse gases (e.g., biological carbon storage and sequestration; methane emissions from wetlands).
Regulating	Catchment integrity	Regulation, by ecosystems, of the quantity, location, and timing of the flow of surface and groundwater used for drinking, irrigation, transport, hydropower, and as the support of non-material contributions. Amelioration, by ecosystems, of the impacts on humans or their infrastructure caused by floods, drought, and other geophysical hazards.
Regulating	Water purification and nutrient cycling	Regulation – through filtration of particles, pathogens, excess nutrients, and other chemicals – by freshwater ecosystems or particular organisms of the quality of water used directly (e.g., drinking, swimming) or indirectly (e.g., aquatic foods, irrigated food and fiber crops, freshwater habitats of heritage value). Regulation, by organisms, of pests, pathogens, predators, or competitors that affect humans (materially and nonmaterially), or freshwater plants or animals of importance for humans. Also the direct detrimental effect of organisms on humans or their plants, animals, or infrastructure.

Food fisheries of the Lower Mekong River Basin

The Lower Mekong River Basin (LMB) supports the largest inland fishery in the world (Figure 2), yielding around 2.3 million metric tons (mt) of fish and other aquatic animals (e.g., frogs, snakes, snails, aquatic insects) per year

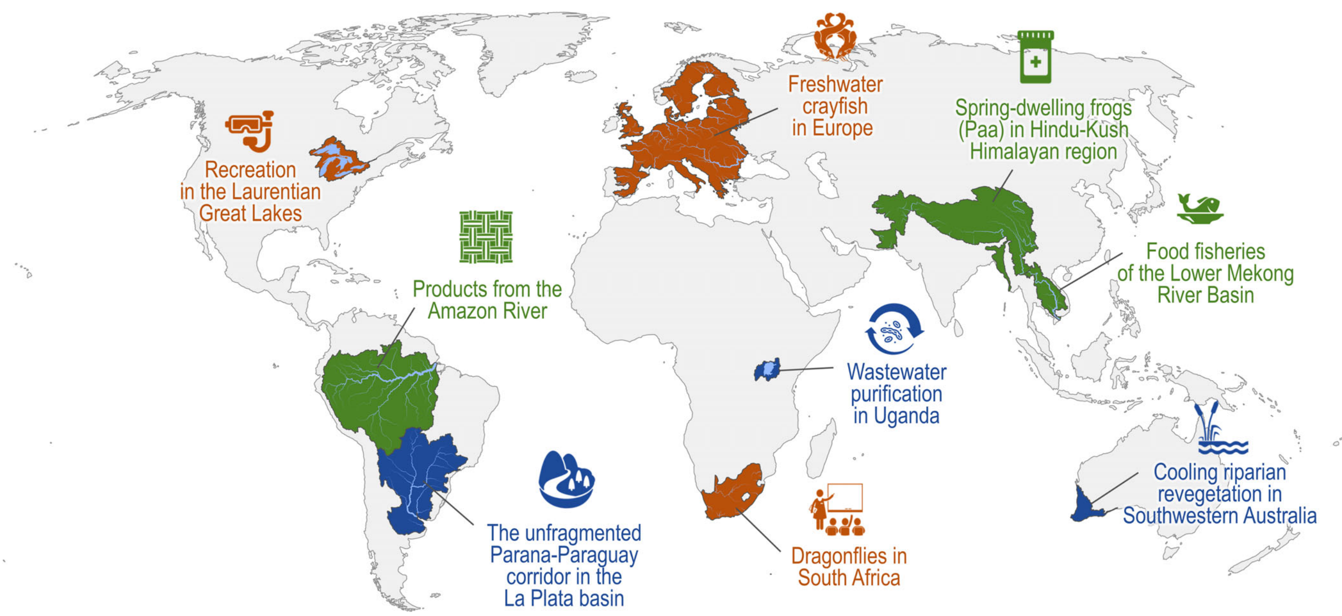

FIGURE 1 Selected case studies representing the suite of critical ecosystem services dependent on freshwater biodiversity (Map data: Department of Agriculture Water and the Environment, 2020; GRDC, 2020; Great Lakes GIS, 2019; ICPAC Geoportal, 2019; IUCN, 2009; Sharma et al., 2019). See Table 1 for symbols and color coding. Note that other geographic regions not featured here are also dependent on ecosystem services from freshwater biodiversity.

(Hortle & Bamrungrach, 2015). This fishery contributes 47%–80% of the annual animal protein intake for the region (34 kg/person/year on average), especially important in rural households where nutrient-rich alternative foods are not readily available (Hortle, 2007). The LMB is one of the world's most biodiverse rivers with at least 877 freshwater fishes, including some of the largest freshwater fish species in the world: the Mekong freshwater stingray *Hemitrygon laosensis*, the giant pangasius *Pangasius sanitwongsei*, and the Mekong giant catfish *Pangasianodon gigas*, the first of which is Endangered and the latter two are Critically Endangered and of Significant Conservation Concern based on the IUCN Red List (Hogan et al., 2004; Tedesco et al., 2017). Many of the species important for LMB food fisheries are migratory. Consequently, hydropower development, among other anthropogenic stressors, threatens both biodiversity and food security in the region (McIntyre et al., 2016; Winemiller et al., 2016). As fishery yields from Africa, Europe, and parts of Asia are highly correlated with freshwater biodiversity, declines in freshwater biodiversity will have substantial ramifications for LMB food security (McIntyre et al., 2016).

4.2 | Health and genetic resources

Freshwater organisms have long provided medicinal, veterinary, and pharmacological products. For hundreds of years, freshwater leeches have been used in medicine (Elliott & Kutschera, 2011) and dentistry (Jha et al., 2015) for cleaning wounds and for stimulating blood flow (i.e., hirudotherapy). More recently, various freshwater model organisms such as the zebrafish *Danio rerio* (Dooley & Zon, 2000), danionin fish *Danionella* spp. (Britz et al., 2021), and the African clawed frog *Xenopus laevis* (Cannatella & de Sá, 1993) have become widely used in the study of human disease. Urodele and anuran amphibians are used in regenerative medicine to investigate the potential for limb growth following musculoskeletal injuries (e.g., amputations; Song et al., 2010). Amphibian skin secretions have been investigated for use in medical and pharmaceutical applications (Clarke, 1997) and there is ethnopharmacological evidence that secretions from an Amazonian frog have been used for millennia by indigenous peoples to treat skin infections (Rodrigues et al., 2012). Also in the Amazon, the fat of the trahira fish *Hoplias mala-baricus* is used to treat earaches (Begossi et al., 2004). Various other fish species such as fathead minnow *Pimephales promelas*, rainbow trout *Oncorhynchus mykiss*, bluegill sunfish *Lepomis macrochirus*, Japanese medaka *Oryzias latipes*, and zebrafish are used in toxicity tests to support identification and characterization of potential hazards of chemicals (Belanger et al., 2013; OECD, 2019). Freshwater plants such as duckweed *Lemna minor* are used for the optimization of human monoclonal antibodies which enable the manufacturing of therapeutic

FIGURE 2 The inland capture fishery of the Lower Mekong River Basin is the world's largest, with diverse and unique gear, such as this one found in Lao PDR (Photo Credit: A. J. Lynch).

proteins free of zoonotic pathogens (Cox et al., 2006). Freshwater blue-green algae are cultured or harvested for nutritional supplements (Sathasivam et al., 2019) and to obtain bioactive compounds (secondary metabolites) that have therapeutic benefits (e.g., as antivirals and anti-inflammatories; Gupta et al., 2013). Collagens derived from various types of freshwater fishes have been applied in surgical dressings, drug delivery, and skin care products (see Olden et al., 2020 and references cited therein). Many of these same applications (from hirudotherapy to use of zebrafish models) have also been extended to veterinary medicine (Nowik et al., 2015; Sobczak & Kantyka, 2014). Macrophytes are also sourced for biochemicals, natural medicines, and pharmaceuticals (Thomaz, 2021). Beyond these benefits, interacting with freshwater species via outdoor activities as well as cultivating and watching live freshwater fishes in an aquarium (see Section 5.3) can reduce stress (Costa-Neto, 2005) and anxiety (Buttelmann & Römpke, 2014) with particular benefits for cardiac-diseased patients to reduce blood pressure (Kongable et al., 1989).

Aquatic genetic resources, that is aquatic plants (i.e., microalgae, macroalgae, and macrophytes), aquatic animals (i.e., fish and aquatic invertebrates) and fungi, help support continuous supplies of food, raw materials, and medicines to humans. According to the UN Convention on Biological Diversity (CBD, 2006), "biological resources include genetic resources, organisms or parts thereof, populations, or any other biotic component of ecosystems with actual or potential use or value for humanity." Sustainable aquaculture often relies on healthy, genetically varied, wild brood stock, which is at risk if these wild stocks decline (FAO, 2019). Wetlands, in particular, are considered to be a tremendous pool of genetic resources (given their diversity and inherent range of phenotypes and genotypes that span the aquatic–terrestrial interface) allowing individuals and populations to adapt or resist to changing environmental conditions including climate change (Convention on Wetlands, 2021). Rapid loss of wetlands would likely jeopardize the genetic resources and thus people's future prosperity (Convention on Wetlands, 2021).

Spring-dwelling frogs (Paa) in Hindu-Kush Himalayan region

The Hindu Kush-Himalayan region covers eight countries from Myanmar in the east to Afghanistan in the west. This region, also known as the Third Pole, is considered the water tower of Asia because it is the source of 10 major Asian rivers that slake the thirst of some 1.9 billion people living downstream (Scott et al., 2019). There is a rich variety of species attributed to a large number of spring sources (Allen et al., 2010; Chettri et al., 2010). These spring sources between 1000 and 3000 m above sea-level are the key habitats of many amphibians including the species of riverine frogs (Figure 3a).

Mountain spring-dwelling frogs of genus *Nanorana*, *Ombrana*, and *Amolops*, commonly known as Paa in Nepal and Northern India, serve as a source of protein and medicine to cure diseases like typhoid, diarrhea, dysentery, stomach ache, urine problems, and piles as well as heal cuts and wounds (Ghosh, 2018; Shrestha & Gurung, 2019; Shrestha & Shah, 2017). Fresh meat or smoked Liebig's paa frog *Nanorana liebigii* is believed to cause a surge of energy and is given as a supplement to sick people, pregnant women, and nursing mothers. Similarly, dried frogs are soaked in water and processed into a smooth paste which is applied to wounds and burns that helps in healing and removing scars (Lohani, 2011). Due to high nutritional and therapeutic values, large numbers of paas are routinely collected (Figure 3b). A study conducted by Shrestha and Gurung (2019) reported that around 50% of the respondents collect 51–100 individual Liebig's paa frogs within a season and trade locally at US$ 0.45–2.26 per individual. A similar set of benefits is provided by *Amolops* spp. where people paste the skin of the frog and use its slime over wounds as a

(a) (b)

FIGURE 3 (a) Springs in western Nepal at 2400 m above sea level are habitat for mountain spring-dwelling paa frogs (Photo Credit: R. D. Tachamo-Shah). (b) Dried Liebig's paa frogs *Nanorana liebigii* are used medicinally for ailments ranging from typhoid to diarrhea, dysentery, stomach ache, urine problems, piles, and open wounds (Photo Credit: Shrestha & Gurung, 2019).

treatment to stop bleeding (Shrestha & Gurung, 2019; Wangyal et al., 2021). As over 80% of livelihoods in the Hindu Kush-Himalayan region depend on ecosystem services, freshwater biodiversity losses have substantial ramifications for local people (Xu et al., 2019).

4.3 | Materials goods

Freshwater organisms contribute in numerous ways to production of materials for clothing, decoration, and ornamental purposes. For example, freshwater fish connective tissue can be made into a glue with prolonged boiling (Bangabandhu et al., 2017); fish oils protect wood, metal, fibers, and concrete and are a key ingredient in lubricants and soaps (McGinnis & Wood, 2007); isinglass (gelatin) made from swim bladders is used as a fining agent during alcohol processing (Eun et al., 1994); and bioplastics are produced from melted scales of fish (Aradhyula et al., 2020). Fish parts are also routinely fashioned into weapons, tools, apparel, jewelry, and musical instruments on all inhabited continents (Olden et al., 2020). Aquatic plant (macrophyte) biomass has been used as fertilizer (Edwards, 1980), in ceramics (Delaqua et al., 2020), and to manufacture concrete blocks (Pereira & Bezerra, 2012). Macrophyte fibers from water hyacinth *Eichhornia crassipes* are also used in the preparation of rustic furniture and the reed totora *Schoenoplectus californicus* is used in the construction of handcrafts, boats, and houses (Thomaz, 2021); the floating islands that are home to the Uros people of Lake Titicaca in the Andes mountains on the border of Bolivia and Peru are built almost entirely from totora culms.

Products from the Amazon River

The Amazon Basin is a biodiversity hotspot with about one-fifth of the world's freshwater discharge and the highest concentration of freshwater biodiversity on earth (Jézéquel et al., 2020). Amazonian fishes represent ∼15% of all described freshwater fish species; local people have heavily relied on these fish for food, income, and material goods. Dried pirarucu fish *Arapaima gigas* tongues are frequently used in small Amazonian villages to grate mandioca root into cassava flour (Figure 4a) as well as dried guaraná into guaranine (i.e., caffeine) for drinks. Pirarucu scales are used as nail files, and piranha fish (family Serrasalmidae) jaws are used as scissors (Olden et al., 2020). Leather from the skin of pirarucu is also used in various consumer products including pants, jackets, wallets, and shoes (Figure 4b). Traditional stringed instruments rely on swim bladder glue and strings made from fish guts. Many fish species are dried and

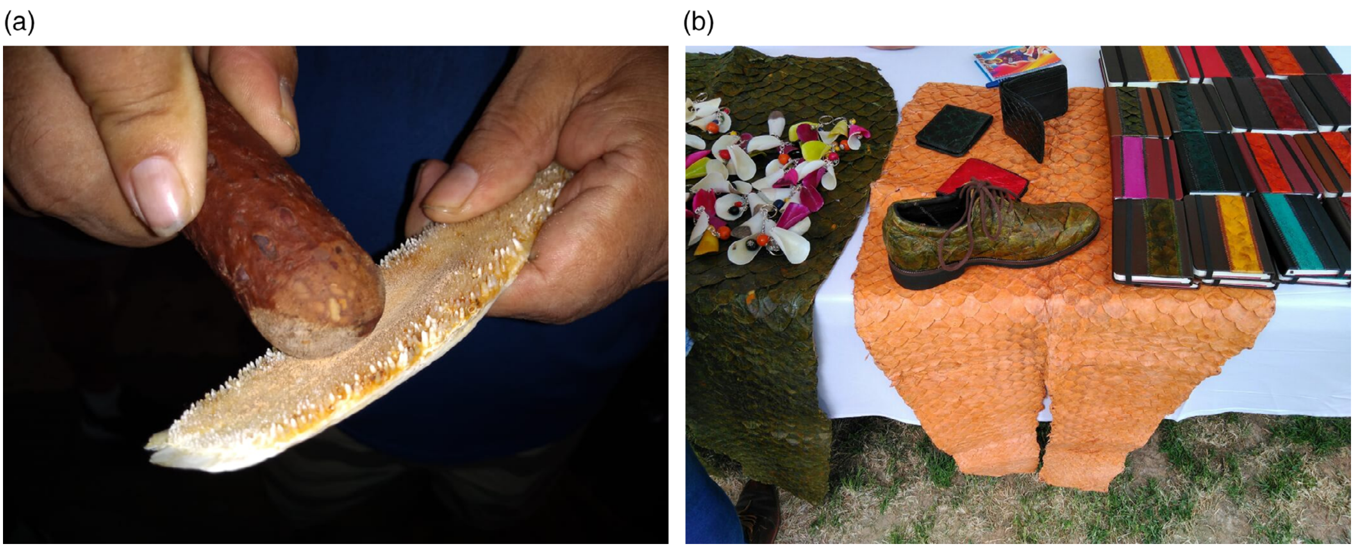

FIGURE 4 (a) Fish parts are fashioned into tools by many human cultures, including in the Amazon where the pirarucu fish *Arapaima gigas* tongue is used as grater for mandioca root to produce cassava flour (Photo Credit: J. Vitule). (b) Fish skins are fashioned into apparel by many human cultures, including in the Amazon where consumer products including wallets, notebooks, and shoes (Photo Credit: J. Vitule).

preserved, displayed as attractions, and sold as souvenirs. The Amazon's freshwater ecosystems and human communities are increasingly at risk as the associated natural resources are threatened. The continued loss of abundant and diverse Amazonian fishes will further compromise the many material goods supported by them.

5 | NON-MATERIAL

5.1 | Culture

Freshwater biodiversity is the basis for a diverse range of cultural services which encompass religious, spiritual, and social–cohesion experiences, playing a key role in supporting people's identities. All of these services can contribute to enrich people's lives in terms of giving meaning, inspiration, and a feeling of belonging or connectedness. Many communities around the world have developed a deeply rooted emotional bond to freshwater ecosystems and biodiversity, which we can see expressed in a diversity of freshwater biodiversity-related traditional customs and rituals (particularly among indigenous rightsholders), but also in a wealth of individual and personal practices including those related to spirituality (He et al., 2021; Wantzen et al., 2016). One such celebration is the Sepik River Crocodile and Arts Festival (https://www.papuanewguinea.travel/events/sepik-river-crocodile-arts-festival) during which the cultural significance of the New Guinea crocodile *Crocodylus novaeguineae* for Papua New Guinea's Sepik River Clans is honored. Species of *Arapaima* (one of the largest freshwater fish on earth) and *Podocnemis* (including four extant species of freshwater turtles) play central roles in the livelihood and cultural identity of many Amazonian peoples (Tavares Freitas et al., 2020). Pacific salmon *Oncorhynchus* spp. have been harvested by Indigenous Peoples of the Northern Pacific Rim for subsistence and livelihoods for over 1000 years (Morin et al., 2021). Sophisticated, sustainable harvest management practices, developed through generations of interdependence with salmon, are based on cultural and spiritual beliefs and stewardship building the centerpiece of these social–ecological systems (Atlas et al., 2021). In Aotearoa, New Zealand, various indigenous freshwater species play an integral part in Māori culture as mahinga kai, a term that relates to species harvest but also knowledge transmission, cultural practice, and access to the environment (Kitson & Cain, 2022). Among these mahinga kai species are the heavily exploited New Zealand longfin eel *Anguilla dieffenbachii* (commonly referred to as tuna by the Māori), giant kōkopu fish *Galaxias argenteus*, kōaro fish *G. brevipinnis*, freshwater mussel kākahi *Echyridella menziesii*, and freshwater crayfish kōura *Paranephrops planifrons* and *P. zealandicus*.

Freshwater crayfish in Europe

The cultural importance of freshwater biodiversity in the history of European countries is proven by their appearance in emblems, coats of arms, toponymies, family names, as part of regional sayings, and as figures in legends and stories. Large-bodied, long-lived freshwater crayfish, which are ecologically important components of freshwater food webs, ecosystem engineers, and keystone species, are also a regionally important resource for food or fodder (Danilovic et al., 2022; Jussila et al., 2021; Patoka et al., 2016). This importance is highlighted through heraldry; the carapace is associated with protection and the claws with the ability to defend. In Christianity, crayfish is considered a religious symbol of being reborn or resurrected, which is attributed to the skin-shedding process, as the animal's chitinous shell does not grow with them. Crayfish could also be consumed during religious fasting (enabling a source of animal protein). Cultural representations are regionally specific; for example, white-clawed crayfish *Austropotamobius pallipes* appears in the coat of arms of Cento (Ferrara, Italy) where crayfishing was one of the main village resources in the 13th century (Gherardi, 2011). Likewise, in Cottbus, Germany, crayfish, abundant in the River Spree which flows through the city, are widely celebrated (Figure 5) and prominently placed on the city's coat of arms (Krestin et al., 2014). Today, the native European crayfish *Astacus astacus* is listed as Vulnerable by the IUCN Red List because, like the white-clawed crayfish (which is Endangered), it is susceptible to crayfish plague carried by the signal crayfish *Pacifastacus leniusculus*, an invasive North American species. Regionally, they may be nearing extinction (Jussila et al., 2021). The cultural connection to these wild organisms is gradually disappearing, reducing information transmission to items only in museums, where it is still largely inaccessible to the communities to which it is culturally relevant. Consequently, the species becomes susceptible to "societal extinction" which may influence perceptions of the natural environment, strengthen shifting baseline syndrome, and hinder conservation efforts (Jarić et al., 2022).

FIGURE 5 Crayfish, particularly the native European crayfish *Astacus astacus*, are integrated into diverse cultural celebrations around Europe, featured on coats of arms, in regional sayings, and statuary as shown here in Cottbus, Germany (Photo Credit: svolks; CC BY-SA 3.0).

5.2 | Education and Science

Freshwater biodiversity provides opportunities through education and science to help humans prosper. Given the importance of freshwater and its biodiversity, it is not surprising that there have been calls for educating the public on these topics (Darwall et al., 2018). Yet, there is also evidence that, although educators recognize the importance of these topics and impart such knowledge on learners, many educators lack sufficient training or knowledge on freshwater systems to be able to effectively teach such materials (Fortner & Meyer, 2000; Payne & Zimmerman, 2010). Nonetheless, from formal curriculum in elementary schools (e.g., raising salmon in the classroom; Granack, 2001) to focused extracurricular youth engagement activities (Torkar & Mohar, 2013), there is evidence that efforts to educate and engage learners about freshwater biodiversity helps to forge connections and a life-long commitment to freshwater conservation, stewardship, and even citizen science (e.g., Dwivedi, 2021). Because freshwater ecosystems occur around the globe, from wilderness to rural and urban environments, there are many opportunities to learn about ecosystem structure and function, interconnections between biotic and abiotic features, and human impacts. The hands-on nature of such learning (often outside of the classroom—such as searching for species in a stream) is inherently fun, helping students to connect with science, technology, engineering, and math (i.e., STEM) topics and recognize that science and conservation are enjoyable and rewarding (Haines, 2016). Fortunately, there is a growing number of resources available to educators (see Fortner, 2001) to help learners engage with aquatic topics (see, e.g., The Nature Conservancy virtual field trips; https://www.nature.org/en-us/about-us/who-we-are/how-we-work/youth-engagement/nature-lab/virtual-field-trips/). Likewise, public aquaria, zoos, parks, and conservation areas worldwide help connect, educate, and inspire the public with freshwater biota (see Murchie et al., 2018 for examples).

Freshwater science provides opportunities to unveil mysteries of life and identify novel applications of freshwater biodiversity to benefit humans. *Daphnia*, an ecologically important freshwater zooplankton genus, is widely used to advance science (e.g., parasitology, Cuco et al., 2020; disease evolution studies, Frenken et al., 2020; evolutionary biology, Govaert et al., 2021; ecotoxicology, Peake et al., 2016). The Amazon molly fish *Poecilia formosa* is a fascinating all-female species that reproduces via gynogenesis (sperm-dependent parthenogenesis) and is used in studies on behavior and collective intelligence (Bierbach et al., 2017; Doran et al., 2022). While these are documented laboratory, mesocosm, and experimental applications, opportunities to gain scientific insight from other aquatic species in natural environments may be diminished if freshwater biodiversity continues to decline.

Dragonflies in South Africa

Freshwater species can provide an educational window to link people and the health of their freshwater environment. For example, dragonflies are widely used in freshwater assessment as they are highly visible and representative of whole assemblage structures sensitive to changes in freshwater conditions (Figure 6a). Indices have been developed, such as the Dragonfly Biotic Index (Samways & Simaika, 2016), enabling civil society of all ages to easily monitor the state and improvement of water bodies by assessing the presence of particular dragonfly species. The extent to which dragonfly assemblages shift in their species composition reflects the changing quality of environmental conditions in streams (e.g., Watson et al., 1982). As environmental conditions deteriorate, there is a shift in the average score of all the dragonfly species present. Importantly, the response seen in the dragonfly assemblage to changing conditions is also reflected in other indicator taxa, such as mayflies, stoneflies, and riverflies and caddisflies (Ephemeroptera, Plecoptera, and Trichoptera, respectively) indicating that the macroinvertebrate community as a whole is shifting according to a decline or improvement in local environmental conditions (Kietzka et al., 2019). The Mini Stream Assessment Scoring System (MiniSASS; http://www.minisass.org/en/) is another citizen science tool in South Africa that utilizes dragonflies and other macroinvertebrates to provide additional opportunities to link communities with official monitoring of waterbodies.

Dragonflies are used in environmental education in many parts of the world, with prime examples from South Africa, Tanzania, and Japan (where they have high cultural significance) (Clausnitzer et al., 2017). In South Africa, to help increase freshwater awareness, dragonflies are featured at botanical gardens including Kirstenbosch National Botanical Garden, Cape Town, hosting over one million visitors per year, and the KwaZulu-Natal National Botanical Garden which has particularly high dragonfly species richness and variety. Children and the elderly were found to engage particularly strongly, enabling an awareness trail to be developed with the aim of encouraging the value of healthy freshwater systems (Niba & Samways, 2006; Suh & Samways, 2001, 2005). To support these efforts, attractive field guides were developed for all the national botanical gardens (Willis & Samways, 2011) as well as one dedicated to the dragonfly trail (Figure 6b; Willis & Samways, 2013).

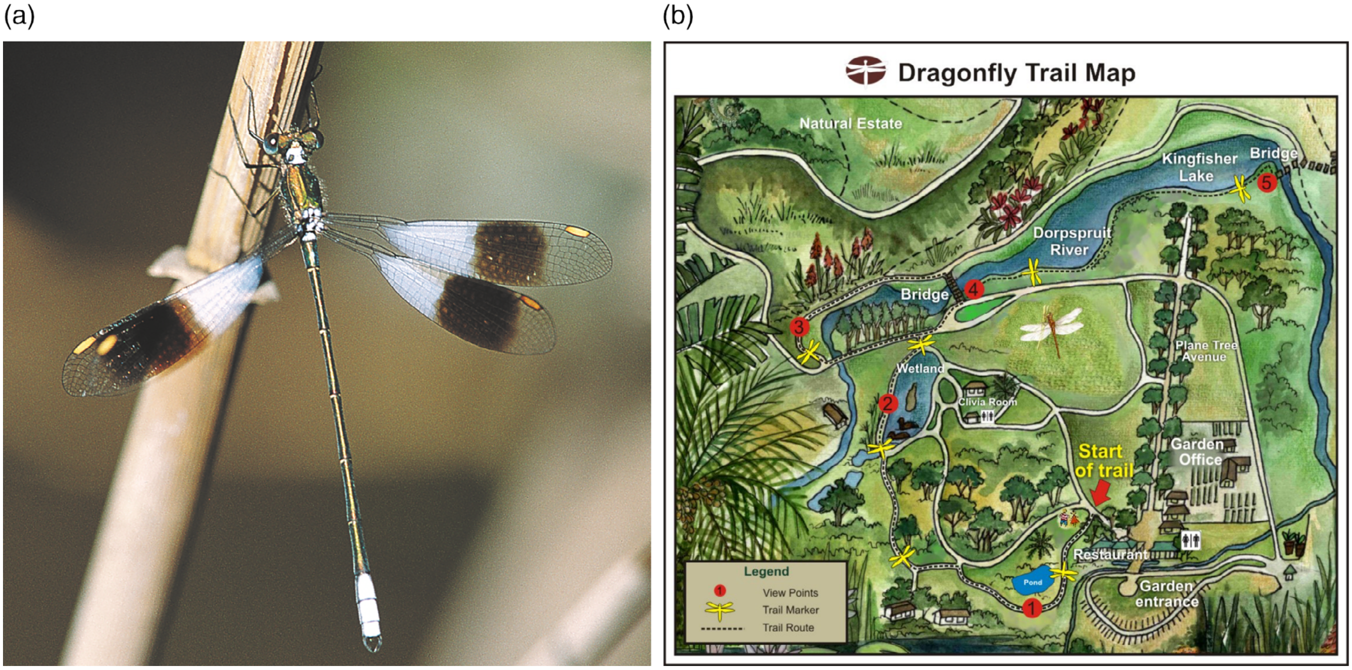

FIGURE 6 (a) Dragonflies, such as the Amatola malachite *Chlorolestes apricans*, an extreme habitat specialist which is highly localized to a few mountains in South Africa, are frequently used in the compilation of habitat quality indices (Photo Credit: M. Samways). (b) As iconic insects, and symbolic of freshwater systems, they are also frequently featured in environmental education trails, such as this dragonfly awareness trail at the KwaZulu-Natal National Botanical Garden, South Africa, which is visited often by school-aged learners (Photo Credit: Willis & Samways, 2013).

5.3 | Recreation

Recreational services supported by freshwater biodiversity within lakes, rivers, wetlands, and the catchment as a whole offer vast opportunities for beneficial activities such as relaxation, leisure, tourism, and aesthetic enjoyment. Angling, wildlife watching, photography, snorkeling, diving, swimming, motorized, and non-motorized boating are some of the most common recreational activities with opportunities to interact with freshwater biodiversity, often reliant on good water quality (Getzner, 2015; Heino et al., 2021; Iis, 2019; Lynch et al., 2021). Indeed, participation in freshwater recreation activities like swimming and boating is often connected to perceived water quality through sensory experiences (i.e., smell and vision) that are directly related to aquatic biota (e.g., excessive algal blooms, sliming on rocks; Barnett et al., 2018; Tienhaara et al., 2021). The collective outdoor pursuits provided by freshwater biodiversity are considered cultural services as defined by the Millennium Ecosystem Assessment (2005) and are linked to human well-being (Thiele et al., 2020). Well-being can include physical, cognitive, and social health benefits and can be based on a number of senses being stimulated (see Ferraro et al., 2020 and the health and genetic resources section above). Recreation is one of the most listed freshwater ecosystem services documented in the literature (see Böck et al., 2018; Hanna et al., 2018; Kaval, 2019; Vári et al., 2021). Beyond human well-being, recreational services often contribute to local and regional economies (e.g., Borisova et al., 2020; Getzner, 2015; Sánchez et al., 2021) and have the potential to engage large numbers of people in and around freshwater bodies. With over 4.55 billion social media users, the opportunity to connect with others through these platforms is powerful, though under-used to promote freshwater biodiversity conservation (He et al., 2021).

Recreational anglers are the main fisheries sector in inland waters of industrialized nations (Cooke et al., 2015). For example, in the United States alone, there are 40.5 million freshwater anglers, 526,600 jobs associated with freshwater fishing, and the industry contributes over US$ 41 billion to the country's gross domestic product (ASA, 2018, 2020). Recognizing this substantial value, the United States codified the Wild and Scenic Rivers Act to take an ecosystem-based approach to valuing and protecting services associated with freshwater biodiversity (Paveglio et al., 2022; Perry, 2017).

Aquarium fish keeping, whether by hobbyists for at home collections or institutions open to the public (i.e., public aquariums or zoos) is a recreational pursuit that is directly dependent on freshwater biodiversity. Indeed, this pursuit encompasses millions of hobbyists worldwide, with an estimated 3–9 million enthusiasts in the United Kingdom alone (Reid et al., 2013). The global trade in ornamental fishes for the aquarium industry is worth US$ 15–30 billion each year, with 90% coming from freshwater fishes (Evers et al., 2019). This trade does present some threats to wild fishes (and to the health of captive-bred fishes). However, in some cases it has prompted sustainable wild and captive fisheries that have helped secure the conservation of the species and their habitats and provided income to impoverished citizens in rural communities, who often have important ethnoknowledge of the ecology of the fishes (da Silva Ladislau et al., 2021), and who might otherwise engage in destructive practices such as mining or logging (see Project Piaba case study in Phang et al., 2019).

Recreation in the Laurentian Great Lakes

The Laurentian Great Lakes make up 84% of North America's surface freshwater and 21% of global surface freshwater. Approximately 34 million people live in the provinces and states surrounding the region and represent 32% and 8% of the Canadian and United States' populations, respectively. Recreating on and around the Great Lakes is an important way for residents to connect with the aquatic environment and the associated flora and fauna (Figure 7a,b). In a recent survey, the top recreational activities included hiking, swimming, diving, boating (non-motorized and motorized), birdwatching, and fishing (IJC, 2021). Indeed, parks around the Great Lakes saw record visitors during the COVID-19 pandemic; for example, Indiana Dunes National Park at the southern tip of Lake Michigan having a 34% increase in attendance in August 2020, compared with the same month in 2019 (Oosthoek, 2020). With 4.3 million boats registered in the eight states surrounding the Great Lakes, this accounts for nearly one-third of all registered boats in the United States alone (Great Lakes Commission, 2007). An estimated 11.88 million recreational boating trips occur annually within the Great Lakes Basin, with 3.8 million originating from Canada, and the other 8.01 million originating from the United States (Fisheries and Oceans Canada, 2017). Fishing is often linked to boating trips and roughly 1.8

FIGURE 7 (a) Recreational bird watchers, such as these two birders on Moonlight Bay, Lake Michigan, in Door County, Wisconsin, enjoy the variety of species found in the Great Lakes; spring is a popular season to watch for migratory species such as buffleheads *Bucephala albeola* and Bonaparte's gull *Chroicocephalus philadelphia* (Photo Credit: K. J. Murchie). (b) Much of Door County has received the designation as "Bird City Wisconsin" for recognizing that healthy communities include healthy natural ecosystems that support birds (photo credit: K. J. Murchie).

million recreational anglers fish the Great Lakes each year (Burkett et al., 2018). Recreational birding opportunities abound in the region and numerous resources exist online to assist people in identifying locations for these activities and what species may be present at various times of years (see Great Lakes Audubon, https://gl.audubon.org/birds/where-to-bird; Great Lakes Nature Conservancy, https://www.nature.org/en-us/about-us/where-we-work/priority-landscapes/great-lakes/stories-in-the-great-lakes/great-lakes-birds/; Long Point Bird Observatory, https://www.birdscanada.org/bird-science/long-point-bird-observatory/). Should freshwater biodiversity suffer in the Great Lakes, a primary draw for recreational tourism would be lost, along with the connection to these incredible water bodies.

6 | REGULATING

6.1 | Catchment integrity

A diverse array of freshwater plants and other organisms can support the ecological integrity of a catchment. Examples include riparian and aquatic plant and tree species, such as sedges, reeds, and rushes, that provide control of runoff, reduce water velocity, enhance bank stability, capture sediment, and filter nutrients and pollutants, benefiting different communities who inhabit lands close to freshwater bodies or use them for various purposes (Tabacchi et al., 2000). Another example is beavers *Castor* spp., which are considered a keystone species due, in part, to their influence on catchment hydrological functioning (i.e., storing water and attenuating up to 60% of average flood flows; Puttock et al., 2021). Beaver dam construction maintains base flows which can ensure downstream hydrological connectivity during low flow or drought periods (Fairfax & Small, 2018).

The unfragmented Parana-Paraguay corridor in the La Plata basin

The Parana-Paraguay corridor in the La Plata basin can be considered a paradigmatic case to understand the importance of preserving biodiversity across an intact aquatic ecosystem as a high-value benefit for society (Baigún & Minotti, 2021). This corridor runs along 3500 km of still unfragmented riverscapes, where free-flowing conditions allow longitudinal, lateral, and vertical exchanges, fluxes, and transference of organic matter, nutrients, and organisms. The Parana-Paraguay corridor is enhanced by still well-preserved floodplain wetlands composed of aquatic plant species including *Eysenhardtia crassipes, E. polystachya, Ludwigia peloides, Polygonum acuminatum, P. elephantipes*, *P. ferrugineum*, *P. prionitis*, and *P. repens*. Flood pulses trigger reorganization of the biotic communities and successional processes across the floodplain. The release of compact aquatic vegetation masses, known as "camalotales" (i.e., floating islands on river) or "embalsados" (i.e., masses of floating water plants) establish new plant populations in the riparian succession, while also transporting nutrients, organic matter, seeds, insects, and invertebrates, and providing refuge to numerous fish species (Sabattini & Lallana, 2007).

The composition of fish assemblages also reflects the ecological integrity of the catchment which, as in other neotropical rivers, is characterized by high biomass of detritivorous species (Yossa & Araujo-Lima, 1998). Fish species such as *Prochilodus lineatus*, *Loricaria* spp., *Plecostomus* spp., and *Cyphocharax* spp. play a key ecological role by contributing to the recycling of organic matter and nutrients from sediments (Taylor et al., 2006; Winemiller et al., 2006). As fish assemblages along the Parana-Paraguay corridor include around 40 long-distance migratory species, these species sustain dynamic fluxes and transport of organic matter and nutrients when moving upstream and downstream (Baigún & Minotti, 2021). Beyond catchment integrity, these fishes also support livelihoods and employment for rural communities through small-scale fisheries and high-value recreational fisheries (Figure 8), and they serve as valuable water quality bioindicators (Baigún et al., 2013). They represent an engine for developing local and regional economies. If these important freshwater resources and services are lost, the region could be devastated socially and economically.

6.2 | Climate regulation

Freshwater ecosystems are critical for carbon and methane storage and sequestration through vegetation cover, photosynthesis, and regulation of aerosols. Algae and macrophytes, especially vegetated wetlands, play a substantial role in capture and storage of atmospheric carbon in the form of living plant tissues and decomposed vegetation (Kayranli et al., 2010). Other species like freshwater fungi or microbes are less visible but have been found to be essential

FIGURE 8 Artisanal fisheries in the Parana-Paraguay corridor of the La Plata basin are predominantly supported by migratory species which require free-flowing waterways and ecological integrity (Photo Credit: C. Baigun).

contributors to aquatic food web dynamics (Klawonn et al., 2021) and methane cycling (Günthel et al., 2020). It is estimated that wetland ecosystems contain about 20%–30% of the global carbon pool and contribute a significant role in the atmospheric carbon cycle (Lal, 2008). Other components of fluvial systems such as riparian and floodplain vegetation play a critical role in storing carbon (dos Reis Ferreira et al., 2020). For example, carbon stocks have been estimated at 474 tons of carbon per ha for mature riparian woods and 212 tons of carbon per ha for meadows and reeds in the Danube floodplains (Cierjacks et al., 2010). Diverse riparian canopies can also regulate water temperature (Garner et al., 2017), and the restoration of riparian corridors is recognized as a vital means of landscape and riverscape adaptation to climate change (Capon et al., 2013).

Cooling riparian revegetation in Southwestern Australia

The southwestern corner of the Australian continent is a global biodiversity hotspot; freshwater streams and wetlands support 24 amphibians, a rich freshwater invertebrate fauna, and nine of the 11 native fish species are endemic (Morgan et al., 1998). The region, where average temperatures have already increased by almost 1°C since 1910, is projected to be increasingly hot and dry (Davies, 2010). Increasing water temperature may exceed the upper thermal limits (about 21°C) of sensitive freshwater fauna, especially cold stenotherms such as Ephemeroptera, Plecoptera, and Trichoptera. Upland streams without riparian vegetation are most vulnerable to temperature increases. A model based on climatic conditions, vegetation, water depth, bed materials, and flow (STREAMLINE) has shown that stream shading provided by riparian vegetation and topography (stream banks) could maintain upland streams below the 21°C threshold (Davies, 2010). Protecting natural riparian regrowth and active revegetation using local provenance species form major elements of stream restoration programs to mitigate rising water temperatures in southwestern Australia (Davies & Stewart, 2013; Water and Rivers Commission, 1999). As well as protecting endemic lotic biodiversity and gene banks that may be lost under hotter and drier climatic regimes, healthy riparian zones (Figure 9) help to mitigate the effects of climate change and human activities on valued ecosystem services (Graziano et al., 2022). Riparian shading can reduce light levels and control the growth of nuisance plants and algae, with environmental, water quality, and recreational implications (Barnett et al., 2018). Cooler water transported downstream can improve conditions in more open or cleared areas, thereby limiting adverse effects of warming on fish food resources and thermally regulated lifecycles, even

FIGURE 9 Shading by riparian vegetation, as shown here in the Augustus River, Western Australia, mitigates the effects of increasingly hot and dry conditions on stream temperatures in the southwestern Australian biodiversity hotspot, protecting sensitive cold stenotherms such as mayflies, stoneflies, and riverflies and caddisflies (Ephemeroptera, Plecoptera, and Trichoptera, respectively) and helping cooler water reach downstream to reduce heat stress and fish kills (Photo Credit: S. E. Bunn).

preventing heat stress and fish kills (Bunn & Davies, 2000; Turschwell et al., 2018). The value of these and other ecosystem services associated with riparian diversity, structure, and processes are predicted to increase with climate change (Capon et al., 2013).

6.3 | Water purification and nutrient cycling

Freshwater ecosystems and the biodiversity they contain play an essential role in cleaning water via filtration of excessive nutrients, pathogens, and pollutants. Ostroumov (2004) suggested that freshwater ecosystems can even be termed "bioreactors" describing their relationship with water purification because of their (1) large scale, (2) numerous taxa with diverse roles, and (3) broad range of biocatalytic capabilities. In particular, freshwater organisms can assist with: (1) contaminant biodegradation, (2) accumulation, sequestration, and removal of toxicants, (3) oxidative degradation of contaminants, (4) uptake of biogenic (i.e., nitrogen and phosphorus) and organic (i.e., carbon-based) substances by organisms, (5) production of exometabolites, (6) water filtration and sediment trapping, and (7) formation of pellet and detritus particles and their sedimentation to the river bottom. As an example, wetlands can reduce the concentration of nitrate, which is a threat to safe drinking water and can cause harmful algal blooms; in some cases, by more than 80% as percentage change in inflow-outflow nutrient loading by the wetland (MEA, 2005). Numerous freshwater taxonomic groups (ranging from bacteria and benthic algae to protozoans and macroinvertebrates) are involved in these processes providing some inherent, and important, redundancies within the system. For example, algae and macrophytes readily take up nitrogen and phosphorus from agricultural waste and runoff and can cycle the nutrients back into freshwater ecosystems or even, as in Florida, people recover and reuse the concentrated supplement for high-value microalgae products for biofuel feedstock (Bohutskyi et al., 2016). As another example from West Bengal, India, water hyacinth removes heavy metals and other aquatic plants remove grease and oil to purify 23 million liters of polluted water daily that is used to support fish ponds with one ton of fish harvest per day (Pye-Smith, 1995). No less important, in floodplain rivers, mycorrhizal fungi can contribute to transfer nutrients between aquatic and terrestrial systems between the surface and water table, helping drive establishment and growth of plants which can stabilize islands (Harner et al., 2011).

Wastewater purification in Uganda

Freshwater wetlands have an important role in water purification and nutrient cycling around the world. In East Africa, for example, burgeoning human populations producing uncontrolled waste are threatening the integrity of Lake Victoria (Figure 10a). Phosphorus, which is responsible for eutrophication and production of algal toxins in the lake that can be harmful to people and other organisms, is captured at retention rates between 60% and 90% by vegetation along the edge of the lake (MEA, 2005). The economic value of such processes to human communities is rarely quantified. One well-known example is that of Nakivubo swamp and the Kyetinda wetland near Kampala, Uganda, which receives much of the city's wastewater and filters it before reaching Lake Victoria (Figure 10b). The wastewater purification and nutrient retention services of the swamp are estimated to have an economic value of up to US$ 1.75 million a year (Emerton, 2005). Loss of this service would lead to multiple negative consequences resulting from the eutrophication of Lake Victoria (e.g., fish kills, blue-green algal blooms with associated toxins, fertilization of water hyacinth which is already a major problem), loss of amenity value, and exposure to human fecal bacteria and viruses.

7 | FUTURE-PROOFING WITH FRESHWATER BIODIVERSITY

Freshwater biodiversity patterns can signal environmental stress on aquatic ecosystems, their services, and human well-being (Lynch et al., 2016). Individual species respond, often predictably, to stress arising from eutrophication and pollution, flow modification, habitat degradation, loss of connectivity, non-indigenous species, over-exploitation, and climate change (Capon et al., 2021; Dudgeon et al., 2006; Tickner et al., 2020; Vörösmarty et al., 2010). Freshwater assemblages (e.g., phytobenthos, plants, invertebrates, fish, and even less visible ones like fungi or microbes) integrate individual, multiple, and cumulative effects of environmental stress throughout their catchments (Craig et al., 2017). Community changes associated with changes in certain sentinel assemblages can serve as powerful biological indicators of aquatic ecosystem health or ecological integrity (Karr et al., 1986). Examples include the fish-based Index of Biotic Integrity, the O/E Index (i.e., observed vs. expected community composition and diversity), and the Biological Condition Gradient approach (Davies, 2000; Hughes et al., 2021). New indicators have been proposed for intermittent rivers and ephemeral streams (Pastor et al., 2022). Innovative biodiversity assessment techniques (e.g., remote sensing, eDNA, camera traps, sound recordings, radiotelemetry) and established field methods can document biodiversity patterns at multiple scales (Arthington, 2021). Numerous national monitoring systems have evolved, including protocols of the European Union Water Framework Directive (EU WFD), the U.S. Environmental Protection Agency's National Aquatic Resource Surveys, the South African River Ecostatus Monitoring Programme, China's River Health Index, and the Australian National River Health Programme (reviewed by Dickens et al., 2021). Regional biomonitoring protocols have also proliferated. Expecting future changes in freshwater biodiversity, especially due to changing climates, capacity, and resources, our flexibility to develop, test, and apply new methodologies will be fundamental to help monitor and therefore preserve the ecological integrity of freshwater systems (Tickner et al., 2020). Preserving aquatic ecosystem integrity preserves freshwater biodiversity and all of the important benefits and services that freshwater biodiversity provides to people.

As one example, catchments in Southeast Queensland support varied freshwater habitats and high freshwater biodiversity. Over 800 species of riparian trees, shrubs, vascular aquatic plants, and macroalgae have been recorded, macroinvertebrates are speciose, and 39 native species of freshwater fishes include the endangered Australian lungfish *Neoceratodus forsteri* and fishes of high recreational significance (Arthington et al., 2019). The region's freshwater systems and biodiversity have been central to First Nations well-being for at least 40,000 years, and their services today include cultural values, landscape integrity, potable water, fibers, food, educational opportunities, and recreation. The ecological health of Southeast Queensland waterways is monitored annually by Healthy Land and Water using 16 indicators in five groups (diversity metrics for invertebrates and fish, ecosystem metabolism, water quality, nutrient cycling). Annual report cards, released publicly over 20 years, have fostered community engagement and stewardship of regional waterway health, while regular assessment tracks progress toward agreed river restoration targets

FIGURE 10 (a) As development continues to expand in East Africa, (b) Lake Victoria wetlands, such as the protected Kyetinda wetland, are becoming increasingly important to filter wastewater before it reaches Lake Victoria (Image Credits: (a) Imagery - ©2023 CNES/Airbus, Maxar Technologies; Map data - ©2023 Google; Wetland outline - OpenStreetMap data, modified; and (b) A. Nicol).

(Bunn et al., 2010). Tracking the effects of multiple stressors on the biological diversity and ecosystem integrity of aquatic ecosystems is essential to help bend the curve of freshwater biodiversity decline and inform progress toward achievement of the Post-2020 Global Biodiversity Framework (Arthington, 2021; Dickens et al., 2021; Tickner et al., 2020).

8 | NATURE-BASED SOLUTIONS WITH FRESHWATER BIODIVERSITY

While technical measures, such as dams, canals, dikes, or measures for water treatment are often dominant approaches to water-related socio-ecological challenges, Nature-based solutions (NbS) are measures that "protect, sustainably manage and restore natural or modified ecosystems [...] that simultaneously benefit human well-being and biodiversity" (UNEA, 2022). NbS are well known for sustainable water management measures related to stormwater management, flood protection, urban water pollution control, as well as urban water use for food, water, and energy (Cassin et al., 2021; Volkan Oral et al., 2020). NbS also provide the promise of multifunctionality (i.e., measures provide important contributions to the protection of biodiversity and human well-being beyond their primary intended function; Cohen-Shacham et al., 2016; Faivre et al., 2017; Serra-Llobet et al., 2022; WWDR, 2018). For example, constructed wetlands can support stormwater treatment, pathogen removal, reduced flooding risk, and carbon sequestration (Brix, 2003; Vymazal, 2011).

Some freshwater species are outright ecosystem engineers, implementing NbS themselves. In North America and Europe, beavers have effectively transformed homogeneous landscapes into comparatively species-rich and heterogeneous wetland environments (Law et al., 2017). Their habitat modifications improve riparian habitat, allow waterfowl colonization and/or movement, create amphibian refuges, and open spaces in forested areas to support butterfly, adder, and slow worm habitat requirements (Mckinstry et al., 2002; Nummi & Holopainen, 2014; Willby et al., 2018). At the same time, they connect biotopes, restore rivers and floodplains, improve landscape water budgets as well as water quality due to sediment and nutrient storages, and support flood retention capacity (Maiga et al., 2017; Scholz, 2016; also see Section 6.1 above). Other freshwater biota play a key role in contributing to shoreline stabilization and other vegetation NbS. Riparian revegetation can significantly reduce flooding, soil erosion, and water pollution (Davis & Naumann, 2017). Hydropower facilities even recognize this NbS value, finding it cost-effective to restore and maintain intact shoreline vegetation in upper catchments to prevent erosion, decrease the sediment load to reservoirs, reduce costs for dredging, and increase the lifespan of dams (Boelee et al., 2017).

NbS with freshwater species have already offered much in terms of rethinking urban stormwater management and water pollution. For many decades (if not centuries), planners and engineers devised means of ensuring that precipitation falling in urban areas would be collected and rapidly shunted into engineered (usually concrete) channels that eventually made their way to receiving bodies like rivers and lakes (Brookes, 1988). However, in the past few decades it has become apparent that such efforts actually contribute to flooding and harm freshwater biodiversity (Hey, 1998). Constructed wetlands are one of the most common NbS used as an alternative to control water pollution in cities from rainwater, combined sewer overflow, and outflow from wastewater treatment plants (Hale et al., 2022). Taking this a step further, the "sponge city" concept has been implemented on a large scale in China (Li et al., 2017). Large wetland areas that had once been developed were restored and additional wetlands created with the idea that these features would function like sponges, absorbing runoff and attenuating flood events while creating biodiversity-rich areas within urban centers for people to enjoy (Nguyen et al., 2019). Both natural channel design and sponge cities represent freshwater NbS that have the potential to benefit humans and biodiversity.

9 | FRESHWATER BIODIVERSITY FOR THE "FUTURE WE WANT"

Our overview focuses on the benefits that indigenous freshwater biodiversity supplies to people and nature. While beyond the scope of this exercise, we acknowledge the complex relationships and extensive nuance when accounting for the positive contributions of non-indigenous species (Sax et al., 2022). Undoubtedly, freshwater biodiversity conservation, human livelihoods, and sustainable development are closely linked, yet there is an increasing awareness that international policy agreements, and water resource management in general, have overlooked the importance of freshwater biodiversity and the severe and widespread threats to it (Arthington, 2021; C. Dickens et al., 2020; Elliott et al., 2022). Fresh water has been "managed more as a physical resource vital to survival rather than as the special and delicate habitat that it provides for an extraordinary array of organisms" (Lovejoy, 2019). Yet, the failure to recognize that freshwater biodiversity is intertwined with the ability of freshwater ecosystems to provide services makes it difficult to future-proof. We are at a critical point to address this blindness to the full importance of freshwater ecosystems, in the development of future policies and management, from regional to national and global scales (van Rees et al., 2021).

The "future we want" (UN, 2012) can be captured by the targets of the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework, provided the development and implementation of that Framework treats freshwater ecosystems in an equitable way to the terrestrial ecosystems through which they flow. It has been a significant challenge to achieve an explicit mentioning of inland waters in several of the Framework Targets and away from a simple discussion of "land and seas," as realized in the Conference of the Parties 15 agreement in December 2022. Given the scale and speed of losses in the diversity, range, and abundance of river, lake, and wetland species, and given the distinctive set of pressures and drivers causing those losses, this provides a timely opportunity to address these Targets as well as adapt language and communications for other international bodies (e.g., IPBES). With better recognition of the benefits people receive from freshwater biodiversity, effective conservation, strategic protection, and tactical restoration can minimize the extinction risk for freshwater species (Darwall et al., 2018). To realize a sustainable vision of the future, people need freshwater biodiversity to maintain this critical suite of ecosystem services.

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CONFLICT OF INTEREST

Sonja C. Jähnig is a Senior Editor for *WIREs Water*. No other authors have any conflicts to declare.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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