Knowl. Manag. Aquat. Ecosyst. 2022, 423, 19
© T. Oberdorff, Published by EDP Sciences 2022
https://doi.org/10.1051/kmae/2022017

www.kmae-journal.org

Knowledge &
Management of
Aquatic
Ecosystems

Journal fully supported by Office
français de la biodiversité

OPINION PAPER OPEN ACCESS

Time for decisive actions to protect freshwater ecosystems from global changes

Thierry Oberdorff*

UMR EDB (Laboratoire Évolution et Diversité Biologique), CNRS 5174, IRD253, UPS; 118 route de Narbonne, F-31062 Toulouse, France

Received: 23 February 2022 / Accepted: 9 June 2022

Abstract – Freshwater ecosystems and their biodiversity provide fundamental services to humans such as nutritional resources production, water provisioning, water purification, recreation, and more globally climate regulation. Anthropogenic impacts on freshwater ecosystems and their biodiversity are already strong and will most probably increase in the near future. Anthropogenic drivers are widely known and include in particular, climate change, habitat shrinking and/or modification due to land-use (*e.g.* water abstraction for human and agricultural consumption, urbanization), habitat fragmentation and homogenization in stream flow dynamics due to the damming of rivers, introduction of non-native species, dumping of nutrient or organic loadings increasing eutrophication processes, and biodiversity over-exploitation. Here, I review the current and future effects of these anthropogenic drivers on freshwater ecosystems and their biodiversity and provide some few examples of existing solutions, either technological, nature-based or policy-based, that could be applied globally to halt and/or minimize their negative consequences. However, success will require systemic changes across public policy and a sufficient political will to do so.

Keywords: Inland waters / biodiversity / global change / conservation

1 General context

Throughout their existence as a species, humans have manipulated and/or transformed nature and natural resources (living and non-living nature) to produce various materials they needed to adapt to variable environmental conditions on Earth. Through progressive technological advances obtained by increasing energy production and consumption, this has allowed to achieve better living standards on average and to sustain the growing human population worldwide, but at the expense of strong social and economic inequalities (Messerli *et al.*, 2019). However, by exploiting natural resources, humans have produced unprecedented impacts on the physical, chemical and biological makeup of our planet compared to pre-human dynamics. These negative tendencies mostly happened during the late Holocene due to large-scale human changes in technologies and increasing dispersal and demography (Louys *et al.*, 2021; Nogué *et al.*, 2021). Currently, human adaptive strategies and the current pace of its population growth both indirectly over-contribute to global changes and the consequent loss of biological diversity (Crist *et al.*, 2017; Sage, 2020) and this non-sustainable exploitation of natural resources, mainly coming until recently from highly industrialized countries, may ultimately threaten the existence of humankind itself (Crist *et al.*, 2017; Human Development Report, 2020). These impacts are clearly demonstrated for many critical elements of our physicochemical environment that act as direct drivers of biodiversity changes (Fig. 1).This factual situation will continue to threaten the Earth's climate system and biodiversity by altering species ranges and abundances, reshuffling biological communities, restructuring food webs and ecosystem functions and generating negative feedbacks to human well-being at the end, especially in developing countries hosting the highest biodiversity on Earth and the most vulnerable people (Shin *et al.*, 2019; Human Development Report, 2020; Thomas, 2020). Thus, without further efforts to counteract current overexploitation, habitat loss and degradation in parallel with climate change, global biodiversity will continue to decline (Arneth *et al.*, 2020) with strong impacts on societal systems (Shin *et al.*, 2019).

2 Overview of current threats to freshwater biodiversity and ecosystems

Freshwater ecosystems provide fundamental services to humans such as food, water, nutrient retention, recreation, and climate regulation (Albert *et al.*, 2021).

---

*Corresponding author: `thierry.oberdorff@ird.fr`

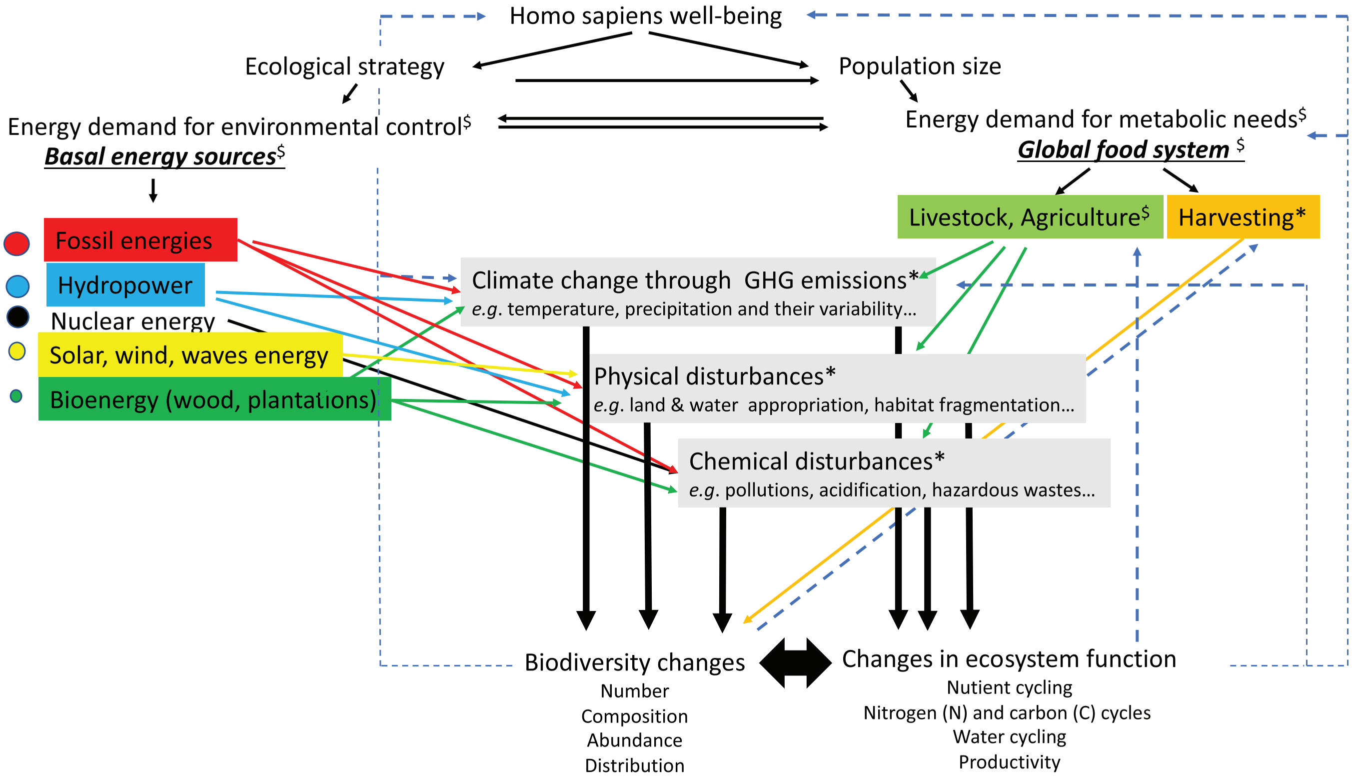

Fig. 1. Direct and indirect drivers of biodiversity changes due to human strategy for environmental control and population expansion (*i.e.* socio-cultural processes). * Direct drivers, $ indirect drivers through human production of goods and services (*e.g.* infrastructure development, industry, transport). Circles for energy sources are proportional to their current degree of use. Line arrows indicate direct links, while dotted arrows indicate feedback effects. Under the proposed scheme two broad interlinked compartments are responsible for climate and biodiversity changes, *i.e.* the basal energy sources and the global food system. Both should be tackled jointly to avoid failures in proposing soundful solutions for climate, biodiversity and human well-being issues, all the more as even if fossil fuel emissions were stopped immediately, current emission trends in global food systems would likely preclude meeting the Paris Agreement goals (Clark *et al.*, 2020).

Globally, freshwaters cover ~1% of Earth's surface with over 60% of this being permanent water bodies and the remaining being seasonally intermittent (Pekel *et al.*, 2016). Considering flowing waters only, the percentage of intermittence is even greater when analyzing the worldwide river network length (~60%, Messager *et al.*, 2021). Despite their rather marginal representation of the Earth's surface, freshwaters are home to approximately 10% of all described species of fungi, plants, invertebrates, and vertebrates on Earth (Kopf *et al.*, 2015). The relative contribution of freshwater ecosystems to global biodiversity is thus extremely high. As a flagship and well-studied example, species of bony fishes (*Actinopterygii*) inhabiting rivers and lakes (~1% of Earth's surface) are as numerous as the ones inhabiting the seas (71% of the Earth's surface; Tedesco *et al.*, 2017a; Dudgeon, 2019) (Fig. 2a). The natural (physical) fragmentation and heterogeneity of running water habitats and geographic isolation of water bodies are most probably involved in explaining this astonishing diversity of species and associated biological traits through positive effects on species speciation rates (*e.g.* Dias *et al.*, 2013; Tedesco *et al.*, 2017b; Albert, Tagliacollo and Dagosta, 2020; but see Miller 2021 for a contrasting explanation). Indeed, as biological exchange among freshwater water bodies is restricted by terrestrial barriers, freshwater habitats are kind of remote islands having experienced specific speciation processes (*e.g.* Hugueny *et al.*, 2010; Dudgeon, 2019). As a consequence, freshwater bodies usually display high degrees of taxa endemism (*e.g.* Tisseuil *et al.*, 2013).

Current major threats to freshwater biodiversity include climate change, habitat modification and pollution from land-use, habitat fragmentation and flow regime homogenization by dams, non-native species, water abstraction for industry or irrigation, and over-exploitation of natural populations (*e.g.* reviewed in Carpenter *et al.*, 2011; Stendera *et al.*, 2012; Dudgeon, 2019). Those threats and their interactions currently affect freshwater biodiversity and functioning to varying degrees (Vörösmarty *et al.*, 2010; Dias *et al.*, 2017; Su *et al.*, 2021; Albert *et al.*, 2021) and their additive and potentially synergistic effects will continue to threaten biodiversity in the future (Knouft and Ficklin, 2017; Carmona *et al.*, 2021). Recognition of this adverse situation has stimulated applied research in developing local grain (*e.g.* site grain) studies. Results from most of these studies analyzing impact of different stressors on freshwater biodiversity show without ambiguity – but most often difficulties in separating individual effects – that human pressure has globally disturbed local assemblages in their biodiversity (*e.g.* population decline, local extinctions), structure and functions with habitat loss and alteration, hydrologic modification, water pollution and

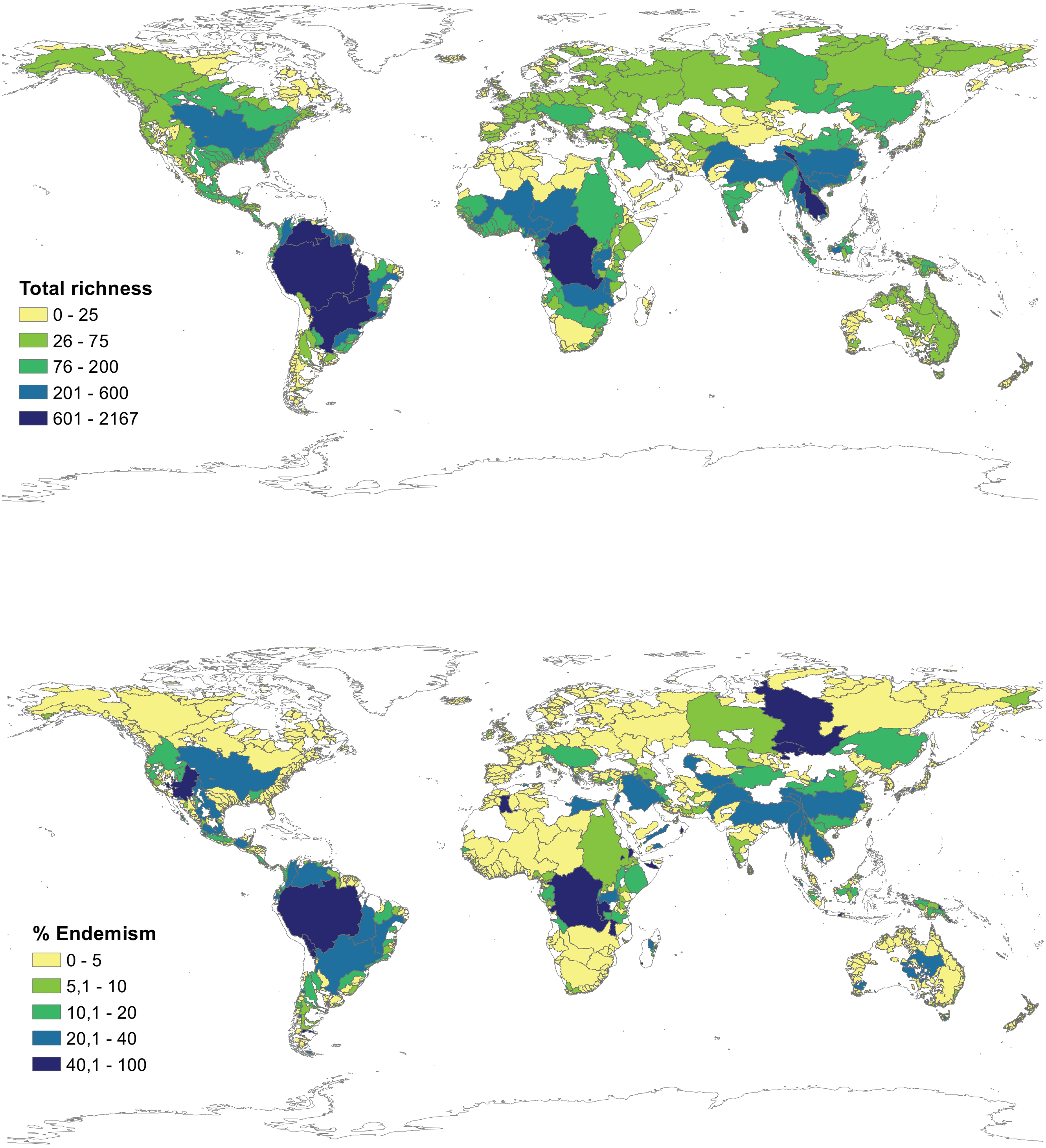

Fig. 2. Global freshwater fish species richness and % of endemic richness patterns at the drainage basin grain (after Tedesco *et al.*, 2017a).

biological invasions being the major drivers of change (reviewed in Carpenter *et al.*, 2011; Stendera *et al.*, 2012). Results are less straightforward when increasing the grain size (*e.g.* river basins, lakes, regions) in part because there has been little effort to evaluate effects of anthropogenic factors at these grains and at large extents due to limitations in data availability (Joppa *et al.*, 2016). The few studies performed at these larger grains at global or continental extents most often conclude that natural geographical factors still dominate over anthropogenic pressures in explaining species richness and community structure, and this for most water bodies and biological models analyzed (*e.g.* Brucet *et al.*, 2013; Feld *et al.*, 2016). Taking as an example a well-studied biological model (*i.e.* freshwater fishes), only water pollution (*i.e.* nutrient enrichment) through eutrophication processes, habitat fragmentation by dams and presence of non-native species have been shown to significantly, although weakly, alter overall biodiversity and the structure and function of communities in lakes (Brucet *et al.*, 2013) and river basins (Blanchet *et al.*, 2010; Villéger *et al.*, 2011; Dias *et al.*, 2017) at continental and/or global extents (but see Su *et al.*, 2021 who found that fish communities have been affected both functionally and phylogenetically by anthropogenic fragmentation and introduction of non-native species in half of the world river systems). Worldwide, the major problem at this time seems, however, the loss of freshwater species and the alteration of aquatic community structure and ecosystem functioning at the local grain (Stork, 2010). Moreover, current evidence shows that anthropogenic factors such as land-use change and pollution, habitat fragmentation, invasive species and overexploitation, are currently and consistently more important in driving biodiversity threats than the contemporary effects of climate change (Tedesco *et al.*, 2013; Dobson *et al.*, 2021; Caro *et al.*, 2022).

3 Current and future climate change threats

Climate is one of the primary driver underlying patterns of biodiversity on Earth, indirectly acting on dispersal, speciation and extinction processes through "water–energy dynamics" (*e.g.* Hawkins *et al.*, 2003; Field *et al.*, 2009). Climate and biodiversity are so closely tied that it is not a real surprise that distributions of Earth's species are changing at accelerating rates with human driven climate change. Scientific evidence is accumulating that many freshwater aquatic species are responding to warming by elevational and/or northward shifts in their distribution ranges, tracking climate warming velocities (Hickling *et al.*, 2005; Comte *et al.*, 2013; Pecl *et al.*, 2017). However, there is also evidence that species range shifts are idiosyncratic and habitat dependent (Lenoir *et al.*, 2020) and these differential species responses to warming promote and will continue to promote reshuffling of communities and consequent cascading effects on food webs and ecosystem functioning, affecting regional availability of food for humans, particularly in developing countries (*e.g.* local fisheries, Ojea *et al.*, 2020).

Besides increasing water acidification (Thomas *et al.*, 2022), climate change alters freshwater ecosystems and their biodiversity by changing (1) temperatures, (2) water availability and (3) flow regimes through changes in precipitation (Doll and Zhang, 2010; Knouft and Ficklin, 2017) and/or temperature (Blöschl *et al.*, 2017). Increased water temperatures often lead to progressive shifts in the structure and composition of assemblages because of changes in species metabolic rates, body size, migration timing, recruitment, range size and interactions (Parmesan, 2006; Scheffers *et al.*, 2016; Pecl *et al.*, 2017; Rosenzweig *et al.*, 2008; Daufresne *et al.*, 2009; Myers *et al.*, 2017). There is already evidence of regional and continental shifts in freshwater organism distributions following their thermal niches (Comte *et al.*, 2013; Mouton *et al.*, 2022), local extirpations through range contractions at the warm edges of species' ranges (Wiens, 2016), body size reductions (Daufresne *et al.*, 2009), and increased incidence of emerging infectious diseases (Reid *et al.*, 2019; Borgwardt *et al.*, 2020). Warmer water temperatures also enhance microorganism metabolism and processing of organic matter (unless dissolved oxygen is limiting), promoting eutrophication when nutrient levels are high (Carpenter *et al.*, 2011; Mantyka-Pringle *et al.*, 2014), and greater omnivory. Warming also induces phenological mismatches between consumers and resources in highly seasonal environments, potentially destabilizing food chain structure (Woodward *et al.*, 2010; Shipley *et al.*, 2022). Moreover, increase in water temperature and streamflow alterations by climate change may interact with land-use modifications to increase autotrophic productivity (Bernhardt *et al.*, 2022) and the dominance of species that prefer warm- and slow-water habitats, reorganizing the structure of freshwater communities (Comte *et al.*, 2021).

Scenarios of climate change (*e.g.* the four Representative Concentration Pathways scenarios (RCPs) 2.6 (most optimistic), 4.5, 6.0, 8.5 (most pessimistic); van Vuuren *et al.*, 2011) on global freshwater ecosystem biodiversity and functioning were reviewed by Settele *et al.* (2014). The strongest temperature increases are projected for eastern North America (0.7–1.2 °C for RCP 2.6 and 8.5 for 2050s), Europe (0.8–1.2 °C), Asia (0.6–1.2 °C), southern Africa (>2.0 °C for RCP8.5) (van Vliet *et al.*, 2016) and Australia (https://soe.environment.gov.au/theme/built-environment/topic/2016/increased-extreme-weather-events#table-BLT5). Moderate water temperature increases (<1.0 °C) are predicted for South America and Central Africa (van Vliet *et al.*, 2016). Changes in water temperature are projected to lead to local or regional population extinctions for cold-water species because of range shrinking especially under the RCP 4.5, 6.0 and 8.5 scenarios (Comte and Olden, 2017). Most lowland-tropical freshwater species are expected to tolerate warmer conditions where water is sufficient (Comte and Olden, 2017).

Decreased water availability and altered flow regimes reduce habitat size and heterogeneity. This increases population extinction rates because the probability of species extinctions increases with reduced habitat size (Tedesco *et al.*, 2013; Barbarossa *et al.*, 2021). Climate change also alters flow regime seasonality and variability (*e.g.* Döll and Zhang, 2010; Blöschl *et al.*, 2017) and increases flow intermittence (Pyne and Poff, 2017). This leads to decreased food chain lengths through loss of large-bodied top predators (Sabo *et al.*, 2010), altered nutrient loading and water quality (Woodward *et al.*, 2010), and/or pushing taxa into novel trajectories from which they may not recover (Bogan and Lytle, 2011). However, whatever the RCP scenario, impacts on the timing of seasonal streamflow are found to be generally small (Eisner *et al.*, 2017), minimizing the possible future impact of this driver on freshwater biodiversity. On the other hand, relative to water availability and according to the wet-wetter/dry-dryer mechanism (Held and Soden, 2006; Gudmundsson *et al.*, 2017; Wang *et al.*, 2017) more severe water stress in current drylands is expected in the future. Although water availability distributions will change little under RCP 2.6 by the end of the 21st century, RCP 4.5, 6 and 8.5 scenarios project substantial drainage shrinking where semi-arid and Mediterranean climates currently occur. Reduced water availability in those regions, including shifts from permanence to intermittence, will generate population extirpations of all types of freshwater organisms (Jaeger *et al.*, 2014), leading to global net biodiversity losses because endemism is usually high in those regions. For example, projected fish extinction rates from drainage shrinking under the SRES A2 scenario (comparable to RCP 8.5) in 1010 river basins worldwide showed that among the 10% most-altered basins, water availability loss will increase background extinction rates by 18.2 times in 2090 (Tedesco *et al.*, 2013). Also, in glacier-fed high-mountain ecosystems, significant changes to snow and glacier melt regimes, including glacier retreat or disappearance, have already been observed (Leadley *et al.*, 2014) and are expected to continue (Kraaijenbrink *et al.*, 2017). This currently, but temporarily, leads to increase the species richness of generalist taxa in glacier-adjacent habitats (positively impacting biodiversity at a regional scale), as well as extinction of endemic ≪ glacier specialist ≫ taxa (negatively impacting total biodiversity at the global scale) (Cauvy-Fraunié and Dangles, 2019).

4 Current and future land-use and water pollution threats

Land-use, especially croplands, mining and urbanization, affect freshwater ecosystems and associated biodiversity through two main pathways. First, water and groundwater withdrawals decrease habitat (water) availability for freshwater organisms leading to increased population extinction rates in rivers and lakes or direct extinctions from riparian zones, wetland, floodplains, and peatland conversions (Gardner *et al.*, 2015; Minayeva *et al.*, 2017), the problem being exacerbated in semiarid regions where water withdrawals lead to some rivers and lakes routinely drying and consequent species extinctions (Foley *et al.*, 2005). Second, water quality is usually degraded by land-use. Intensive agriculture increases sediment, nutrient (N-rich fertilizers) and pesticide loads to ground and surface waters (Peñuelas and Sardans, 2022). Urbanization and industries also substantially degrade water quality mostly through organic, pharmaceuticals, microplastics or phosphorous loadings, especially where wastewater treatment is absent. Mining leads to increased loadings of toxic metals, salts and acids (Johnson and Hallberg, 2005). Part of these chemical cocktails also promote freshwater salinization (Cunillera-Montcusí *et al.*, 2022; Hintz *et al.*, 2022). Such pollutants lead to direct local mortality, impaired individual development and health through bioaccumulation particularly in top predators (Carpenter *et al.*, 2011), altering the structure of biological communities and, consequently, the functioning of aquatic systems (Muturi *et al.*, 2017). For example, (1) pharmaceutical pollution may compromise development and reproduction of aquatic animals by altering behavior and feeding rate of individuals (*e.g.* Brodin *et al.*, 2013) or feminize populations (*e.g.* Kidd *et al.*, 2007); (2) freshwater salinisation may compromise the performance of organisms by causing osmoregulation stress (*e.g.* Cunillera-Montcusí *et al.*, 2022); (3) ingestion of microplastics can cause adverse impacts on growth and development and feeding or reproductive behavior in a range of aquatic biota such as fish, zoobenthos, zooplankton and mollusks (*e.g.* Meng *et al.*, 2020); (4) Nutrient loadings progressively increase eutrophication, depleting oxygen, killing animals, extirpating submerged macrophytes and producing algal blooms (including toxic varieties of cyanobacteria; Paerl and Paul, 2012) and were the leading cause of hypoxia across European lakes since 1850 (Jenny *et al.*, 2016).

Furthermore, deforestation, a key component of land-use change, severely disrupts flooding, thermal regimes, organic matter processing and food web dynamics (Sweeney *et al.*, 2004), exacerbating the establishment and spread of pests and pathogens, especially in tropical regions (Morris *et al.*, 2016). Finally, the loss of lateral hydrological connectivity between rivers and their floodplains through flood-control infrastructures (*e.g.* levees) to satisfy human demand for freshwater and infrastructure development, not only decreases habitat availability but also affects food webs and threatens species that benefit from facultative ontogenetic niche shifts between floodplain and main channel, jeopardizing at the end the entire ecosystem productivity (Opperman *et al.*, 2009; Stoffels *et al.*, 2022).

Concerning freshwater habitats, future RCP projections predict an increase (in order of diminishing importance RCPs 2.6, 6, 8.5) or a decrease (RCP 4.5) in cropland area, an increase (RCP 8.5) or a decrease (in order of diminishing importance RCPs 6, 4.5, 2.6) in grassland area and an increase (RCPs 4.5, 6) or a decrease (RCPs 2.6, 8.5) of natural vegetation area (van Vuuren *et al.*, 2011), but see Alexander *et al.*, (2017) for slightly different projections. The RCP 4.5 scenario, predicting a decrease of land-use area globally, minimizes future freshwater biodiversity disturbances, followed by RCPs 2.6, 6.0 and 8.5 in decreasing order. However, global scenarios mask continental dissimilarities. For example, projections of future primary vegetation show major decreases in western and middle Asia (scenarios 2.6, 6.0 and 8.5), Australia (only RCP 2.6) and North America (only RCP 8.5; Settele *et al.*, 2014).

Concerning water pollution, this anthropogenic pressure has been considerably reduced during the last decades in Australia, North America and Western Europe (Vörösmarty *et al.*, 2010), except for pharmaceuticals, biocides and microplastics because of ineffective treatment currently available (Eerkes-Medrano *et al.*, 2015; Ebele *et al.*, 2017; Wilkinson *et al.*, 2022). Reduced water pollution will benefit freshwater biodiversity whatever the scenario. However, Sinha *et al.* (2017) projected increased eutrophication induced by increased precipitation from climate change in some regions, and Olivier *et al.* (2017) noticed no decrease in nutrient concentrations (except a slight decrease in total nitrogen) for most Northeast U.S. lakes between 1990 and 2013 despite attempts to reduce diffuse pollution. If there is little technology transfer to developing countries, then water pollution will increase worldwide, particularly in tropical regions because of increased human density notably in Asia and Africa, which is expected to account for over half of global population growth between 2015 and 2050 (United Nations, 2015). Under RCP 2.6–if much agricultural, mineral and bioenergy production relocates from high-income to low-income regions, pollution, freshwater biodiversity and aquatic ecosystem functioning will further worsen in those regions (Albert *et al.*, 2021).

5 Current and future habitat fragmentation threats

Dams provide the most characteristic example of anthropogenic fragmentation.

This stressor alters rivers, floodplain lakes, wetlands and estuaries. Dams transform river basins by creating artificial lakes locally, fragmenting river networks, and greatly distorting natural patterns of sediment transport and seasonal variations in water temperatures and flows (Latrubesse *et al.*, 2017; Flecker *et al.*, 2022). Altered flow seasonality in rivers has led to less diverse fish assemblages, decreased inland fisheries production, less stable bird populations and lower riparian forest production (Jardine *et al.*, 2015; Kingsford *et al.*, 2017; Sabo *et al.*, 2017; Ngor *et al.*, 2018). Sediment retention by dams leads to delta recession (Luo *et al.*, 2017; Kondolf *et al.*, 2022) and to degraded coastal fisheries and tropical mangrove forests due to consequent coastal erosion (Ezcurra *et al.*, 2019). Dams also prevent upstream-downstream movement of freshwater plants (*e.g.* Jansson *et al.*, 2000) and animals (e.g. Pess *et al.*, 2014), facilitate settlement of non-native species (Johnson *et al.*, 2008), and increase risks of water-borne diseases and cause local species extirpations by modifying productivity in created reservoirs (Poff and Schmidt, 2016). The fragmentation of river corridors by dams also reduces population sizes and gene flows of aquatic species, increasing species extinction risks (Dias *et al.*, 2017; Brauer and Beheregaray, 2020). Dams are mainly concentrated in highly industrialized regions, but future hydropower development will be concentrated in developing countries and emerging economies (Zarfl *et al.*, 2015; Winemiller *et al.*, 2016; Moran *et al.*, 2018; Schwarz, 2020). Hydropower is expected to expand worldwide whatever the RCP scenario. Most hydropower plants are currently situated in regions where considerable declines in streamflow are projected, resulting in mean reductions in usable hydropower capacity (Turner *et al.*, 2017; van Vliet *et al.*, 2016). Those regions may increase dam building to compensate for the losses unless other energy options are implemented (Zarfl *et al.*, 2015). Also, population density is continuously increasing and will reach around 10 billion in 2050 (United Nations, 2015). This will increase demands for hydropower globally, and especially in tropical regions (Winemiller *et al.*, 2016) where freshwater biodiversity is concentrated (Tisseuil *et al.*, 2013).

6 Current and future non-native species introduction threats

Although policies have been implemented to prevent new introductions globally, the increase in numbers of non-native species shows no sign of saturation over time (Seebens *et al.*, 2017). Non-native species may compete with and/or prey upon native species, generating occasional local population extirpations (Carpenter *et al.*, 2011). Non-native species may also alter ecosystem structure and function (*e.g.* Non-native species are currently changing the functional traits structure of most freshwater fish assemblages worldwide, which may affect ecosystem properties; Blanchet *et al.*, 2010; Toussaint *et al.*, 2018), spread infectious diseases and sometimes may degrade ecosystem services and economies (Leung *et al.*, 2002). They are a key contributor to biotic homogenization of freshwater ecosystems globally (Villéger *et al.*, 2011). Many non-native species are predicted to spread worldwide in the next decades, mainly because of climate change, accelerated economic exchanges among countries, construction of new transportation corridors and increased aquaculture (Seebens *et al.*, 2017).

Anthropogenic disturbances (including climate change) coupled with introductions of non-native species have been associated with native species extirpations and/or range reductions in lakes, reservoirs and rivers (Bell *et al.*, 2021; Zhang *et al.*, 2022). Because both pressures are expected to persist in the 21st century, further threatening of aquatic species is expected.

However, whether non-native species, when introduced, will become invasive (and thus potentially harmful for native communities) or not, is highly context dependent (*e.g.* Manchester and Bullock, 2001).

7 Current and future harvesting threats

Current estimates of inland fisheries harvest are greatly underestimated (Deines *et al.*, 2017), but inland fisheries provide food for billions and livelihood for millions of people worldwide (FA0, 2016), especially in developing countries. Low-income food-deficient countries account for ~80% of the total reported harvest from inland capture fisheries (Lynch *et al.*, 2016). Most global harvesting is concentrated in 16 countries, which have annual inland catches >200,000 tons and together represent 80% of the world's total (FAO, 2016). Asian countries represent 63% of global total catches and African nations >13%. Harvests in African and Asian water bodies are already declining, probably because of environmental degradation and overexploitation (FAO, 2016). Given expected human population increases in Africa and Asia, increased harvesting is expected in both continents in the future. As harvesting decreases population densities and large-bodied species, increased fishing pressure will lead to local extirpations of these species and will alter population (including evolutionary genetic; Czorlich *et al.*, 2022), community structures and food web dynamics (McIntyre *et al.*, 2016). These effects will be magnified by interactions with other anthropogenic stressors, including climate change. Rural economies in developing countries will be the most affected as contributions of inland fisheries to economic security are inversely proportional to development level.

8 Perspectives

As reviewed above, anthropogenic factors and associated processes responsible for the decline of freshwater biodiversity are clearly identified since decades and several existing solutions, either technological, nature-based or policy-based, could be applied globally to halt and/or reverse this rapid decline. These solutions can also benefit climate change mitigation and human well-being (Pörtner *et al.*, 2021; Shin *et al.*, 2022; Smith *et al.*, 2022). Some few examples of potential solutions focusing on improving water quality, restoring freshwater connectivity and protecting freshwater systems globally are given below (see, *e.g.* Tickner *et al.*, 2020 and Harper *et al.*, 2021 for a more extensive list of solutions).

8.1 Improve water quality to sustain aquatic life

Options include:

(1) Improving wastewater treatment technologies and water reuse to reduce pollution from domestic and industrial point sources as well as maintaining sustainable water resources (*e.g.* Bailone *et al.*, 2022). Regarding wastewater treatment plants, a special attention should be given to

pharmaceutical and microplastic pollutions that pose a global threat to both biodiversity and human health (Eerkes-Medrano *et al.*, 2015; Wilkinson *et al.*, 2022). New technologies are now available and can be applied to reduce the level discharged (*e.g.* an advanced membrane bioreactor technology (Lares *et al.*, 2018) can remove up to 98% of microplastics concentration in effluents (Meng *et al.*, 2020)); (2) Improving urban development and agricultural practices by stopping wetlands and peatlands conversion for urban development and agriculture expansion and favoring maintenance of riparian zones at the periphery of all water bodies. Indeed, wetlands, peatlands and riparian zones act as buffer areas able to cool water temperature (riparian zones) and to improve the chemical and biological quality of water through filtering nutrients and stopping erosion and consequent sediment loadings (*e.g.* Engle, 2011); (3) Reducing the use of nutrients (nitrogen and phosphorous), pesticides, herbicides and fungicides applied to land as fertilizers or pest management and improving livestock systems and aquaculture practices by reducing the use of veterinary medicines (antibiotics and growth hormones), which move from lands through freshwater ecosystems. For example, water pollution from nutrients (*e.g.* leading to ecosystem eutrophication and consequent hypoxia) occurs when fertilizers are applied at a greater rate than they are fixed by soil particles or exported from the soil profile by plant uptake. Optimizing nutrient inputs to satisfy plant uptake only, should strongly minimize the export of nutrients to freshwaters and associated environmental and biological impacts. In the same way, manure from livestock production should be stored and treated (*e.g.* through anaerobic fermentation), which can produce organic fertilizers and soil conditioners, decreasing at the same time the need for chemical fertilizers; (4) Favoring efficient and well-managed crop irrigation schemes (*e.g.* drip irrigation, Grafton *et al.*, 2018) which can, besides decreasing the amount of water withdrawal, reduce water return flows and therefore the migration of fertilizers and pesticides to adjacent water bodies.

8.2 Safeguard and restore freshwater connectivity

Hydropower is a leading component of current and future renewable energy portfolios in many countries worldwide and construction of large dams is booming in many countries, particularly in developing countries (Zarfl *et al.*, 2015; Winemiller *et al.*, 2016; Moran *et al.*, 2018). However, the hydropower industry needs to recognize the unsustainability of current common practices for biodiversity and people's livelihoods by including in its strategies the negative social and environmental possible impacts where dams are planned (*e.g.* Moran *et al.*, 2018 ; Peters *et al.*, 2021).

Several solutions exist for reducing the loss of functional connectivity for riverine communities due to dam infrastructures (see, for example, results from the *Adaptative Management of Barriers in European Rivers* (AMBER) project – https://amber.international/about/). Some are listed below: (1) Strategic siting of new infrastructures can be made prior to the construction phase by using multi-objective optimization frameworks to identify least impactful projects by balancing, for example, connectivity maintenance with hydropower generation (*e.g.* Almeida *et al.*, 2022; Flecker *et al.*, 2022). For example, Flecker et al. (2022) recently developed a tool to assess a set of environmental parameters for an optimization analysis helping to find the combinations that can achieve energy production targets while minimizing environmental costs in the Amazon basin; (2) New technical solutions for hydropower dams, such as in-stream turbines, can be privileged, when possible, to maintain the natural dynamic of the fluvial system (*e.g.* connectivity, sediment transport, seasonal river flows; Moran *et al.*, 2018 ; Chaudhari *et al.*, 2021); (3) Systematically designing technical solutions (*e.g.* fish passes) to maintain the fluvial system connectivity for aquatic biota for dams of all sizes (Albert *et al.*, 2021); (4) Systematic dam removal can be considered in regions with aging dams render them unsafe or economically not viable (Foley *et al.*, 2017). When removal is not possible, the natural flow regime baseline of riverine ecosystems should be maintained or restore (*e.g.* Acreman *et al.*, 2014). However, hydropower dams represent only a small fraction of artificial barriers disrupting riverine system connectivity, small instream infrastructures such as weirs, culvets and fords actually constituting the main cause of connectivity loss (*e.g.* Belletti *et al.*, 2020). Many of these small barriers are old and obsolete and can thus be removed to restore connectivity, without major technical difficulties nor strong expected conflict between local stakeholders (but see Blanchet and Tedesco, 2021 for a counter-example).

8.3 Expand the network of protected areas

Protected areas (PAs) play a fundamental role in conserving genetics, species and ecosystem diversity, and in ensuring delivery of ecosystem services from natural habitats. Currently around 17% of global inland surface waters are covered by PAs (Bastin *et al.*, 2019), which is in phase with the Strategic Plan for Biodiversity of the Convention on Biological Diversity (CBD), to conserve by 2020 at least 17% of terrestrial and inland water areas. However, current protected areas are far from being geographically uniform (Bastin *et al.*, 2019) and recent proposals converge around protecting 30 per cent of inland water areas by 2030, with appropriate prioritization (*i.e.* geographical and ecological representability, and connectivity) and management improved (https://www.cbd.int/article/draft-1-global-biodiversity-framework). This strategic expansion of PAs could be realized through a consistent framework allowing to identify, in an objective, transparent, and scientifically rigorous way, important areas contributing significantly to the global persistence of biodiversity (*e.g.* Key Biodiversity Areas (KBAs) – https://www.keybiodiversityareas.org/). As protected areas are most often essentially terrestrially defined, protected area networks are also not fully appropriate for managing freshwater ecosystems (*e.g.* Leal *et al.*, 2020) so that it will be important to (1) design these protected areas for the particular spatial and temporal complexities of freshwater ecosystems (Albert *et al.*, 2021), (2) elaborate management plans harmonising nature conservation and human uses objectives (*e.g.* Abarca *et al.*, 2022).

9 Conclusion

The selected potential solutions listed above – most of them well-known since a long time – are largely achievable and several recovery plans and management Agendas to halt and reverse the rapid decline of biodiversity have been recently proposed (*e.g.* Tickner *et al.*, 2020; Harper *et al.*, 2021; van Rees *et al.*, 2021; Maasri *et al.*, 2022). However, success will require systemic changes across public policy. These changes are far from being insurmountable if there is a sufficient political will to do so. In the same way as for climate change, decision makers need to move urgently beyond well-intentioned speeches as it is now time for concrete and decisive actions.

Acknowledgments. I thank Núria Bonada and Astrid Schmidt-Kloiber for the valuable comments on an earlier draft of the manuscript.

Although this paper is partly based on the Reports of the IPBES global assessment on biodiversity and ecosystem services (IPBES, 2019) and of the IPBES-IPCC co-sponsored workshop (Pörter *et al.*, 2020), the views expressed here represent the individual views of the author. The author is Editor-in-Chief of KMAE, but took no part in the peer review and decision-making processes for this paper.

References

Acreman M, Arthington AH, Colloff MJ, *et al.* 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. *Front Ecol Environ* 12: 466–473.

Albert JS, Destouni G, Duke-Sylvester SM, *et al.* 2020. Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio* 50: 85–94.

Albert JS, Tagliacollo VA, Dagosta F. 2020. Diversification of neotropical freshwater fishes. *Annu Rev Ecol Evolut Syst* 51: 27–53.

Alexander P, Prestele R, Verburg PH, *et al.* 2017. Assessing uncertainties in land cover projections. *Glob Change Biol* 23: 767–781.

Almeida RM, Schmitt RJP, Castelletti A, *et al.* 2022. Strategic planning of hydropower development: balancing benefits and socioenvironmental costs. *Curr Opin Environ Sustain* 56: 101175.

Arbaca H, Morán-Ordoñez A, Villero D, *et al.* 2022. Spatial prioritisation of management zones in protected areas for the integration of multiple objectives. *Biodivers Conserv.* https://doi.org/10.1007/s10531-022-02383-z

Arneth A, Shin Y-J, Leadley P, *et al.* 2020. Post-2020 biodiversity targets need to embrace climate change. *Proc Natl Acad Sci* 117: 30882–30891.

Bailone RL, Borra RC, Fukushima HCS, Aguiar LK. 2022. Water reuse in the food industry. *Discover Food* 2.

Barbarossa V, Bosmans J, Wanders N, *et al.* 2021. Threats of global warming to the world's freshwater fishes. *Nat Commun* 12: 1701.

Bastin L, Gorelick N, Saura S, *et al.* 2019. Inland surface waters in protected areas globally: Current coverage and 30-year trends. *PLoS ONE* 14: e0210496.

Bell DA, Kovach RP, Muhlfeld CC, *et al.* 2021. Climate change and expanding invasive species drive widespread declines of native trout in the northern Rocky Mountains, USA. *Sci Adv* 7: 52.

Belletti B, Garcia de Leaniz C, Jones J. *et al.* 2020. More than one million barriers fragment Europe's rivers. *Nature* 588: 436–441.

Bernhardt ES, Savoy P, Vlah ML, *et al.* 2022. Light and flow regimes regulate the metabolism of rivers. *Proc Natl Acad Sci* 119: e2121976119.

Blanchet S, Grenouillet G, Beauchard O, *et al.* 2010. Non-native species disrupt the worldwide patterns of freshwater fish body size: implications for Bergmann's rule. *Ecol Lett* 13: 421–431.

Blanchet S, Tedesco PA. 2021. French vote for river barriers defies biodiversity strategy. *Nature* 594: 26.

Blöschl G, Hall J, Parajka JJ, *et al.* 2017. Changing climate shifts timing of European floods. *Science* 357: 588–590.

Bogan MT, Lytle DA. 2011. Severe drought drives novel community trajectories in desert stream pools. *Freshw Biol* 56: 2070–2081.

Borgwardt F, Unfer G, Auer S, *et al.* 2020. Direct and indirect climate change impacts on brown trout in Central Europe: how thermal regimes reinforce physiological stress and support the emergence of diseases. *Front Environ Sci* 8: 59.

Brauer CJ, Beheregaray LB. 2020. Recent and rapid anthropogenic habitat fragmentation increases extinction risk for freshwater biodiversity. *Evol Appl* 13: 2857–2869.

Brodin D, Jonsson JFM, Klaminder J. 2013. Unintended recipients of antidepressants. *Science* 339: 814–815.

Brucet SA, Pédron S, Mehner T, *et al.* 2013. Fish diversity in European lakes: geographical factors dominate over anthropogenic pressures. *Freshw Biol* 58: 1779–1793.

Carmona CP, Tamme R, Pärtel M, *et al.* 2021. Erosion of global biodiversity across the tree of life. *Sci Adv* 7: eabf2675.

Caro T, Rowe Z, Berger J, Wholey P, Dobson A. 2022. An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. *Conserv Lett* e12868.

Carpenter SR, Stenley EH, Vander Zanden MJ. 2011. States of the World's freshwater ecosystems, physical, chemical and biological changes. *Annu Rev Environ Resour* 36: 75–99.

Chaudhari S, Brown E, Quispe-Abad R, Moran E, Müller M, Pokhrel Y. 2021. In-stream turbines for rethinking hydropower development in the Amazon basin. *Nat Sustain* 4: 680–687.

Cauvy-Fraunié S, Dangles O. 2019. A global synthesis of biodiversity responses to glacier retreat. *Nat Ecol Evol* 3: 1675–1685.

Clark MA, Domingo NGG, Colgan K, *et al.* 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science* 370: 705–708.

Comte L, Buisson LT, Daufresne M, Grenouillet G. 2013. Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. *Freshw Biol* 58: 625–639.

Comte L, Olden JD. 2017. Climatic vulnerability of the world's freshwater and marine fishes. *Nat Climate Change* 7: 718–722.

Comte L, Olden JD, Tedesco PA, Ruhi A, Giam X. 2021. Climate and land-use changes interact to drive long-term reorganization of riverine fish communities globally. *Proc Natl Acad Sci* 118: e2011639118.

Crist E, Mora C, Engelman R. 2017. The interaction of human population, food production, and biodiversity protection. *Science* 356: 260–264.

Cunillera-Montcusí D, Beklioğlu M, Cañedo-Argüelles M, *et al.* 2022. Freshwater salinisation: a research agenda for a saltier word. *Trends Ecol Evol* 37: 440–452.

Czorlich Y, Aykanat T, Erkinaro J, Orell P, Primmer CR. 2022. Rapid evolution in salmon life history induced by direct and indirect effects of fishing. *Science* 10.1126/science.abg5980.

Daufresne M, Lengfeller K, Sommer U. 2009. Global warming benefits the small in aquatic ecosystems. *Proc Natl Acad Sci U S A* 106: 12788–12793.

Deines AM, Bunnel DB, Rogers MW, *et al.* 2017. The contribution of lakes to global inland fisheries harvest. *Front Ecol Environ* 15: 293–298.

Dias MS., Cornu JF., Oberdorff T., Lasso CA, Tedesco PA. 2013. Natural fragmentation in river networks as a driver of speciation for freshwater fishes. *Ecography* 36: 683–689.

Dias MS, Tedesco PA, Hugueny B, *et al.* 2017. Anthropogenic stressors and riverine fish extinctions. *Ecol Indic* 79: 37–46.

Diaz S, Settele J, Brondízio ES, *et al.* 2019. IPBES: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zenodo.3553579.

Dobson A, Rowe Z, Berger J, Wholey P, Caro T. 2021. Biodiversity loss due to more than climate change. *Science* 374: 699–700.

Döll P, Zhang J. 2010. Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrol Earth Syst Sci* 14: 783–799.

Dudgeon D. 2019. Multiple threats imperil freshwater biodiversity in the Anthropocene. *Curr Biol* 29: 960–966.

Ebele AJ, Abou-Helwafa A, Harrad S. 2017. Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerg Contamin* 3: 1–16.

Eerkes-Medrano D, Thompson RC, Aldridge DC. 2015. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Res* 75: 63–82.

Eisner S, Flörke M, Chamorro A, *et al.* 2017. An ensemble analysis of climate change impacts on streamflow seasonality across 11 large river basins. *Clim Change* 141: 401–417.

Engle V. 2011. Estimating the Provision of Ecosystem Services by Gulf of Mexico Coastal Wetlands. *Wetlands* 31: 179–193.

Ezcurra E, Barrios E, Ezcurra P *et al.* 2019. A natural experiment reveals the impact of hydroelectric dams on the estuaries of tropical rivers. *Science Advances* 5: eaau9875.

FAO. 2016. The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. 200 pp. https://www.fao.org/3/i5555e/i5555e.pdf

Feld CK, Birk S, Eme D *et al.* 2016. Disentangling the effects of land-use and geo-climatic factors on diversity in European freshwater ecosystems. *Ecol Indic* 60: 71–83.

Field R, Hawkins BA, Cornell HV, *et al.* 2009. Explaining spatial diversity gradients across scales: a meta-analysis. *J Biogeogr* 36: 132–147.

Flecker AS, Shi Q, Almeida RM, *et al.* 2022. Reducing adverse impacts of Amazon hydropower expansion. *Science* 375: 753–760.

Foley MM, Bellmore JR, O'Connor JE, *et al.* 2017. Dam removal: Listening in. *Water Resour Res* 53: 5229–5246.

Foley JA, Defries R, Asner GP, *et al.* 2005. Global consequences of land-use. *Science* 309: 570–574.

Gardner RC, Finlayson C. 2018. Global Wetland Outlook: State of the World's Wetlands and Their Services to People. Ramsar Convention Secretariat, 2018, Stetson University College of Law Research Paper No. 2020-5. https://ssrn.com/abstract=3261606

Grafton RQ, Williams J, Perry CJ, *et al.* 2018. The paradox of irrigation efficiency. *Science* 361: 748–750.

Gudmundsson L, Seneviratne SI, Zhang X. 2017. Anthropogenic climate change detected in European renewable freshwater resources. *Nat Climate Change* 7: 813–816.

Harper M, Mejbel HS, Longert D, *et al.* 2021. Twenty-five essential research questions to inform the protection and restoration of freshwater biodiversity. *Aquat Conserv* 31: 2632–2653.

Hawkins BA, Field R, Cornell HV, *et al.* 2003. Energy, water, and broad-scale geographic patterns of species richness. *Ecology* 84: 3105–3117.

Held I, Soden B. 2006. Robust responses of the hydrological cycle to global warming. *J Climate* 19: 5686–5699.

Hickling R, Roy DB, Hill JK, Thomas CD. 2015. A northward shift of range margins in British Odonata. *Glob Change Biology* 11: 502–506.

Hintz WD, Arnott SE, Symons CC, *et al.* 2022. Current water quality guidelines across North America and Europe do not protect lakes from salinization. *Proc Natl Acad Sci USA* 119: 9e2115033119.

Hugueny H, Oberdorff T, Tedesco PA. 2010. Community ecology of river fishes: a large-scale perspective. In: *Community ecology of stream fishes: concepts, approaches and techniques* (Eds. D. Jackson & K. Gido). *American Fisheries Society Symposium* 73: 29–62.

Human Development Report. 2020. The next frontier Human development and the Anthropocene. http://hdr.undp.org/sites/default/files/hdr2020.pdf

IPBES. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E.S. Brondizio, J. Settele, S. Díaz, and H.T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673

Jaeger KL, Olden JD, Pelland LA. 2014. Climate change poised to threaten hydrologic connectivity and endemic fishes in dryland streams. *Proc Natl Acad Sci U S A* 111: 13894–13899.

Jansson R, Nilsson C, Renöfält B. 2000. Fragmentation of riparian floras in rivers with multiple dams. *Ecology* 81: 899–903.

Jardine TD, Bond NR, Burford MA, *et al.* 2015. Does flood rhythm drive ecosystem responses in tropical riverscapes? *Ecology* 96: 684–692.

Jenny J-P., Francus P, Normandeau A, *et al.* 2016. Global spread of hypoxia in freshwater ecosystems during the last three centuries is caused by rising local human pressure. *Glob Change Biol* 22: 1481–1489.

Johnson DB, Hallberg KB. 2004. Acid mine drainage remediation options: a review. *Sci Total Environ* 338: 3–14.

Johnson PTJ, Olden JD, Vander Zanden RJ. 2008. Dam invaders: impoundments facilitate biological invasions into *freshwaters*. *Front Ecol Environ* 6: 357–363.

Joppa LN, O'Connor B, Visconti P, *et al.* 2016. Filling in biodiversity threat gaps. *Science* 352: 416–418.

Kidd KA, Blanchfield PJ, Mills KH, *et al.* 2007. Collapse of fish population after exposure to a synthetic estrogen. *Proc Natl Acad Sci* 104: 8897–8901.

Kingsford RT, Bino G, Porter JL. 2017. Continental impacts of water development on waterbirds, contrasting two Australian river basins: Global implications for sustainable water use. *Global Change Biol* 23: 4958–4969.

Kondolf GM, Schmitt RJP, Carling PA, *et al.* 2022. Save the Mekong delta from drowning. *Science* 376: 583–585.

Knouft JH, Ficklin DL. 2017. The potential impacts of climate change on biodiversity in flowing freshwater systems. *Annu Rev Ecol Evol Syst* 48: 111–133.

Kopf RK, Finlayson CM, Humphries P, Sims NC, Hladyz S. 2015. Anthropocene baselines: assessing change and managing biodiversity in human-dominated aquatic ecosystems. *BioScience* 65: 798–811.

Kraaijenbrink PDA, Bierkens MFP, Ludz AF, Immerzeel WW. 2017. Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature* 549: 257–260.

Lares M, Ncibi MC, Sillanpää M, Sillanpää M. 2018. Occurrence, identification and removal of microplastic particules and fibers in conventional activated sludge process and advanced MBR technology. *Water Res* 133: 236–246.

Latrubesse EM, Arima EY, Dunne T, *et al.* 2017. Damming the rivers of the Amazon basin. *Nature* 546: 363–369.

Leadley P, Proença V, Fernández-Manjarrés J, *et al.* 2014. Interacting regional scale regime shifts for biodiversity and ecosystem services. *BioScience* 64: 665–679.

Leal CG, Lennox GD, Ferraz SFB, *et al.* 2020. Integrated terrestrial-freshwater planning doubles conservation of tropical aquatic species. *Science* 370: 117–121.

Lenoir J, Bertrand R, Comte L, *et al.* 2020. Species better track climate warming in the oceans than on land. *Nat Ecol Evol* 4: 1044–1059.

Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proc Royal Soc B* 269: 2407–2413.

Louys J, Bradje TJ, Chang C-H, *et al.* 2021. No evidence for widespread island extinctions after Pleistocene hominin arrival. *Proc Natl Acad Sci* 118: e2023005118.

Luo XX, Yang SL, Wang RS, Zhang CY, Li P. 2017. New evidence of the Yangtze delta recession after closing the Three Gorges dam. *Sci Rep* 7: 41735.

Lynch AJ, Cooke SJ, Deines AM, *et al.* 2016. The social, economic, and environmental importance of inland fish and fisheries. *Environ Rev* 24: 115–121.

Maasri A, Jähnig SC, Adamescu MC, *et al.* 2022. A global agenda for advancing freshwater biodiversity research. *Ecol Lett* 25: 255–263.

McIntyre PB, Liermann CAR, Revenga C. 2016. Linking freshwater fishery management to global food security and biodiversity conservation. *Proc Natl Acad Sci* 113: 12880–12885

Manchester SJ, Bullock JM. 2001. The impacts of non-native species on UK biodiversity and the effectiveness of control. *J Appl Ecol* 37: 845–864.

Mantyka-Pringle CS, Martin TG, Moffatt DB, Linke S, Rhodes JR. 2014. Understanding and predicting the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish. *J Appl Ecol* 51: 572–581.

Meng Y, Kelly FJ, Wright SL. 2020. Advances and challenges of microplastic pollution in freshwater ecosystems: a UK perspective. *Environ Pollut* 256: 113445.

Messager ML, Lehner B, Cockburn C, *et al.* 2021. Global prevalence of non-perennial rivers and streams. *Nature* 594: 391–397.

Messerli P, Murniningtyas E, Eloundou-Enyegue P, *et al.* 2019. The Future is Now-Science for Achieving Sustainable Development. https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf

Miller EC. 2021. Comparing diversification rates between lakes, rivers, and the sea. *Evolution* 75: 2055–2073.

Minayeva TY, Bragg OM, Sirin AA. 2017. Towards ecosystem-based restoration of peatland biodiversity. *Mires and Peat* 19: Article 01, 1–36.

Moran EF, Lopez MC, Moore N, *et al.* 2018. Sustainable hydropower in the 21th century. *Proc Natl Acad Sci* 115: 11891–11898.

Morris AL, Guégan JF, Andreou D, *et al.* 2016. Deforestation-driven food-web collapse linked to emerging tropical infectious disease, *Mycobacterium ulcerans*. *Sci Adv* 2: e1600387.

Mouton T, Leprieur F, Floury M, *et al.* 2022. Climate and land-use driven reorganisation of structure and function in river macroinvertebrate communities. *Ecography* 2022: e06148.

Muturi EJ, Donthu RK, Fields CJ, Moise IK, Kim C-H. 2017. Effect of pesticides on microbial communities in container aquatic habitats. *Sci Rep* 7: 44565.

Myers SS, Smith MR, Guth S, *et al.* 2017. Climate change and global food systems: potential impacts on food security and undernutrition. *Annu Rev Public Health* 38: 259–277.

Ngor PB, Legendre P, Oberdorff T, Lek S. 2018. Flow alterations by dams shaped fish assemblage dynamics in the complex Mekong-3S river system. *Ecol Indic* 88: 103–114.

Nogué S, Santos AMC, Birks HJB, *et al.* 2021. The human dimension of biodiversity changes on islands. *Science* 372: 488–491.

Ojea E, Lester SE, Salgueiro-Otero D. 2020. Adaptation of fishing communities to climate-driven shifts in target species. *One Earth* 2: 544–556.

Olivier SK, Collins SM, Soranno PA, *et al.* 2017. Unexpected stasis in a changing world: Lake nutrient and chlorophyll trends since 1990. *Global Change Biology* 23: 5455–5467.

Opperman JJ, Galloway GE, Fargione J, *et al.* 2009. Sustainable Floodplains Through Large-Scale Reconnection to Rivers. *Science* 326: 1487–1488.

Paerl HW, Paul VJ. 2012. Climate change: Links to global expansion of harmful cyanobacteria. *Water Research* 46: 1349–1363.

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. *Annu Rev Ecol Evol System* 37: 637–669.

Pecl GT, Arajo MB, Bell JD, *et al.* 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human wellbeing. *Science* 355: 1389.

Pekel JF, Cottam A, Gorelick N, Belward AS. 2016. High-resolution mapping of global surface water and its long-term changes. *Nature* 540: 418, 422.

Peñuelas J, Sardans J. 2022. The global nitrogen-phosphorous imbalance. *Science* 375: 266–267.

Pess GR, Quinn TP, Gephard SR, Saunders R. 2014. Re-colonization of Atlantic and Pacific rivers by anadromous fishes: linkages between life history and the benefits of barrier removal. *Rev Fish Biol Fish* 24: 881–900.

Peters R, Berlekamp J, Lucía A, *et al.* 2021. Integrated impact assessment for sustainable hydropower planning in the Vjosa catchment (Greece, Albania). *Sustainability* 13: 1514.

Poff NR, Schmidt JC. 2016. How dams can go with the flow. *Science* 353: 1099–1100.

Pörtner H-O., Scholes RJ, Agard J, *et al.* 2021. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change; IPBES secretariat, Bonn, Germany, https://10.5281/zenodo.4659158.

Pyne MI, Poff NL. 2017. Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Glob Change Biol* 23: 77–93.

Reid AJ, Carlson AK, Creed IF, *et al.* 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol Rev* 94: 849–873.

Ripple WJ, Wolf C, Newsome TM, *et al.* 2021. World scientists' warning of a climate emergency 2021. *BioScience* 71: 894–898.

Rosenzweig C, Karoly D, Vicarelli M, *et al.* 2008. Attributing physical and biological impacts to anthropogenic climate change. *Nature* 453: 353–357.

Sabo JL, Finlay JC, Kennedy T, Post DM. 2010. The role of discharge variation in scaling of drainage area and food chain length in rivers. *Science* 330: 965–967.

Sage RF. 2020. Global change biology: A primer. *Global Change Biology* 26: 3–30.

Scheffers BR, De Meester L, Bridge TCL, *et al.* 2016. The broad footprint of climate change from genes to biomes to people. *Science* 354: 719–732.

Schwarz U. 2020. Hydropower Projects on Balkan Rivers – 2020 Update. RiverWatch & EuroNatur, Vienna/Radolfzell, 33 pp. https://riverwatch.eu/en/balkanrivers/news/hydropower-projects-balkan-rivers-2020-update.

Seebens H, Blackburn TM, Dayer EE, *et al.* 2017. No saturation in the accumulation of alien species worldwide. *Nat Commun* 8: 14435.

Settele J, Scholes R, Betts R, *et al.* 2014. Terrestrial and Inland Water Systems – In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271–359. https://www.ipcc.ch/report/ar5/wg2/terrestrial-and-inland-water-systems/.

Shin Y-J., Arneth A, Chowdhury RR, *et al.* 2019. Plausible futures of nature, its contributions to people and their good quality of life. In IPBES, 2019. Global Assessment on Biodiversity and Ecosystem Services. (p. 264). https://www.ipbes.net/global-assessment.

Shin Y-J., Midgley G.F., Archer E, *et al.* 2022. Actions to halt biodiversity loss generally benefit the climate. *Glob Change Biol*. https://doi.org/10.1111/gcb.16109.

Shipley JR, Twining CW, Mathieu-Resuge M, *et al.* 2022. Climate change shifts the timing of nutitional flux from aquatic insects. *Curr Biol* 32: 1342–1349.

Sinha E, Michalak AM, Balaji V. 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. *Science* 357: 405–408.

Smith P, Arneth A, Barnes DKA, *et al.* 2022. How do we best synergize climate mitigation actions to co-benefit biodiversity? *Glob Change Biol* https://doi.org/10.1111/gcb.16056.

Stendera S, Adrian R, Bonada N, *et al.* 2012. Drivers and stressors of freshwater biodiversity patterns across different ecosystems and scales. *Hydrobiologia* 696: 1–28.

Stoffels RJ, Humphries P, Bond NR, Price AE. 2022. Fragmentation of lateral connectivity and fish population dynamics in large rivers. *Fish Fish* https://doi.org/10.1111/faf.12641.

Stork NE. 2010. Re-assessing current extinction rates. *Biodivers Conserv* 19: 357–371.

Su G, Logez M, Shengli Tao JX, Villeger S, Brosse S. 2021. Human impacts on global freshwater fish biodiversity. *Science* 371: 835–838.

Sweeney BW, Bott TL, Jackson JK, *et al.* 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *Proc Natl Acad Sci* 101: 14132–14137.

Tedesco PA, Oberdorff T, Cornu JF, *et al.* 2013. A scenario for impacts of water availability loss due to climate change on riverine fish extinction rates. *J Appl Ecol* 50: 1105–1115.

Tedesco PA, Beauchard O, Bigorne R, *et al.* 2017a. A global database on freshwater fish species occurrence in drainage basins. *Sci Data* 4: 170141.

Tedesco PA, Lévêque C, Paradis E, Hugueny B. 2017b. Explaining global-scale diversification patterns in actinopterygian fishes. *J Biogeogr* 44: 773–783.

Thomas CD. 2020. The development of Anthropocene biotas. *Philos Trans Roy Soc B: Biol Sci* 375: 20190113.

Thomas A, Ramkumar A, Shanmugam A (2022). CO_2 acidification and its differential responses on aquatic biota: a review. *Environ Adv* 8: 100219.

Tickner D, Opperman JJ, Abell R, *et al.* 2020. Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. *BioScience* 70: 330–342.

Tisseuil C, Cornu JF, Beauchard O, *et al.* 2013. Global diversity patterns and cross-taxa convergence in freshwater systems. *J Anim Ecol* 82: 365–376.

Toussaint A, Charpin N, Beauchard O, *et al.* 2018. Non-native species led to marked shifts in functional diversity of the world freshwater fish faunas. *Ecol Lett* 21: 1649–1659.

Turner SWD, Ng JY, Galleli S. 2017. Examining global electricity supply vulnerability to climate change using high-fidelity hydropower dam model. *Sci Total Environ* 590-591: 663–675.

United Nations, Department of Economic and Social Affairs, Population Division. 2015. World Population Prospects: The 2015 Revision. New York: United Nations. https://www.un.org/en/development/desa/publications/world-population-prospects-2015-revision.html.

van Rees CB, Waylen KA, Schmidt-Kloiber A, *et al.* 2021. Safeguarding freshwater life beyond 2020: Recommendations for the new global biodiversity framework from the European experience. *Conserv Lett* 14: e12771.

van Vliet MTH, Wiberg D, Leduc S, Riahi K. 2016. Power generation system vulnerability and adaptation to changes in climate and water resources. *Nat Clim Change* 6: 375–380.

van Vuuren DP, Edmonds J, Kainuma M, *et al.* 2011. The representative concentration pathways: an overview. *Climatic Change* 109: 5–31.

Villéger S, Blanchet S, Beauchard O, Oberdorff T, Brosse S. 2011. Current and future patterns of freshwater fish homogenization over the globe. *Proc Natl Acad Sci* 108: 18003–18008.

Vörösmarty CJ, McIntyre PB, Gessner MO, *et al.* 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555–561.

Wang X, Edwards RL, Auler AS, *et al.* 2017. Hydroclimate changes across the Amazon lowlands over the past 45,000 years. *Nature* 541: 204–207.

Wiens JJ, 2016. Climate-related local extinctions are already widespread among plant and animal species. *Plos Biol* 14: e2001104.

Winemiller KO, McIntyre PB, Castello L, *et al.* 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* 351: 128–129.

Wilkinson JL, Boxall ABA, Kolpin DW, *et al.* 2022. Pharmaceutical pollution of the world's rivers. *Proc Natl Acad Sci* 119: 8e2113947119.

Woodward G, Perkins DM, Brown RE. 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philos Trans Royal Soc B* 365: 2093–2106.

Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K. 2015. A global boom in hydropower dam construction. *Aquat Sci* 77: 161–170.

Zhang S, Zheng Y, Zhan A, Dong C, Zhao J, Yao M. 2022. Environmental DNA captures native and non-native fish community variations across the lentic and lotic systems of a megacity. *Sci Adv* 8: eabk 0097.

Cite this article as: Oberdorff T. 2022. Time for decisive actions to protect freshwater ecosystems from global changes. *Knowl. Manag. Aquat. Ecosyst.*, 423, 19.