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2 Freshwater ecosystems under threats with global change

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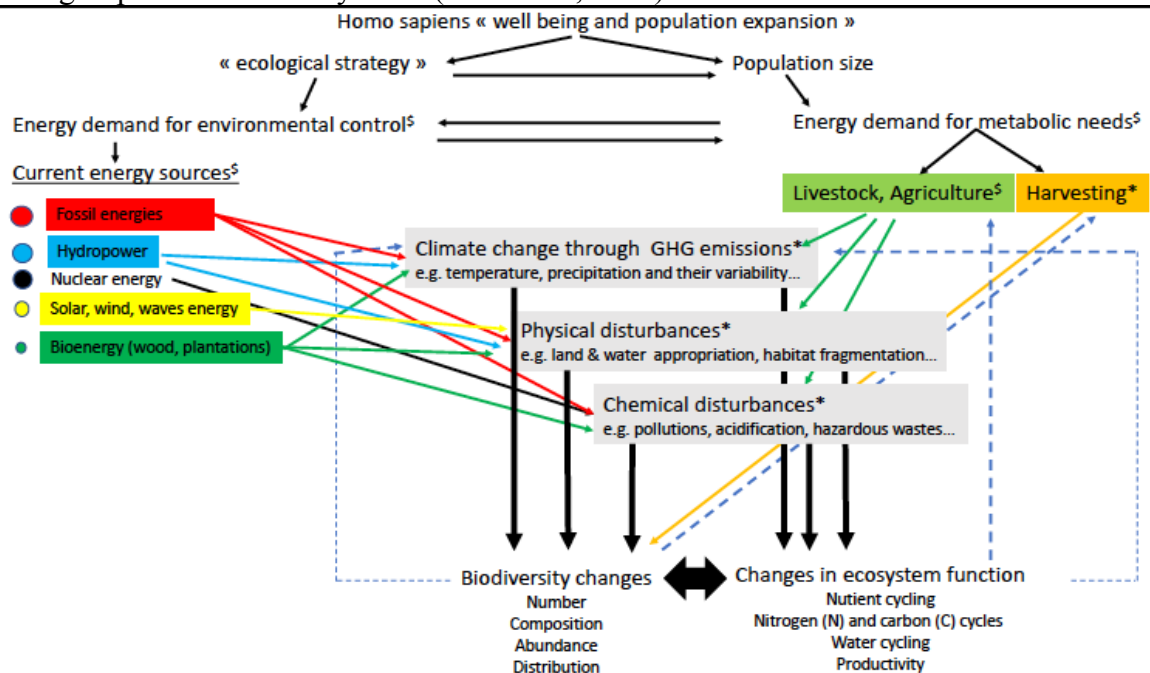
11 **Abstract**

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

28 **General context**

29 Throughout their existence as a species, humans have manipulated and/or transformed
30 nature and natural resources (living and non-living nature) to produce various
31 materials they needed to adapt to variable environmental conditions on
32 Earth. Through progressive technological advances obtained by increasing energy
33 production and consumption, this has allowed to achieve better living standards on
34 average and to sustain the growing human population worldwide, but at the expense
35 of strong social and economic inequalities (Messerli *et al.*, 2019). However, by
36 creating structures of greater internal energy out of the natural resources used, humans
37 have produced unprecedented impacts on the physical, chemical and biological
38 makeup of our planet compared to pre-human dynamics. These negative tendencies
39 mostly happened during the late Holocene due to large-scale human changes in
40 technologies and increasing dispersal and demography (Louys *et al.*, 2021; Nogué *et*
41 *al.*, 2021). Currently, Human adaptive strategy and the current pace of its growth both

42 indirectly over-contribute to global changes and the consequent loss of biological
 43 diversity (Crist *et al.*, 2017; Sage, 2020) and this non-sustainable exploitation of
 44 natural resources, mainly coming until recently from highly industrialized countries,
 45 may ultimately threaten the existence of humankind itself (Crist *et al.*, 2017; Human
 46 Development Report, 2020). These impacts are clearly established for many critical
 47 elements of our physicochemical environment that act as direct drivers of biodiversity
 48 changes, *e.g.* increase in greenhouse gas concentrations (*e.g.* CO₂) and consequent
 49 climate changes and ocean and freshwater acidification, land, freshwater and coastal
 50 appropriation and transformation (*e.g.* land conversion to farms and pastures,
 51 urbanization, river systems artificialization, water withdrawal for industry or
 52 irrigation, coastal engineering and land reclamation), pollution (*e.g.* fertilizers,
 53 pesticides, plastics) and alteration of global nitrogen (N) and carbon (C) cycles
 54 through feedback loops with biodiversity (*e.g.* Arneth *et al.*, 2020; Ripple *et al.*, 2021;
 55 Sage, 2020) (Figure 1). These previous elements and their interactions, together with
 56 overexploitation of natural populations (*e.g.* overhunting, overfishing, overlogging)
 57 have and will continue to threaten the Earth's climate system and biodiversity by
 58 altering species ranges and abundances, reshuffling biological communities,
 59 restructuring food webs and ecosystem functions and generating at the end negative
 60 feedbacks to human well-being, especially in developing countries hosting the highest
 61 biodiversity on Earth and the most vulnerable people (Shin *et al.*, 2019; Human
 62 Development Report, 2020; Thomas, 2020). Thus, without further efforts to
 63 counteract current overexploitation, habitat loss and degradation in parallel with
 64 climate change, global biodiversity will continue to decline (Arneth *et al.*, 2020) with
 65 strong impact on societal systems (Shin *et al.*, 2019).



66

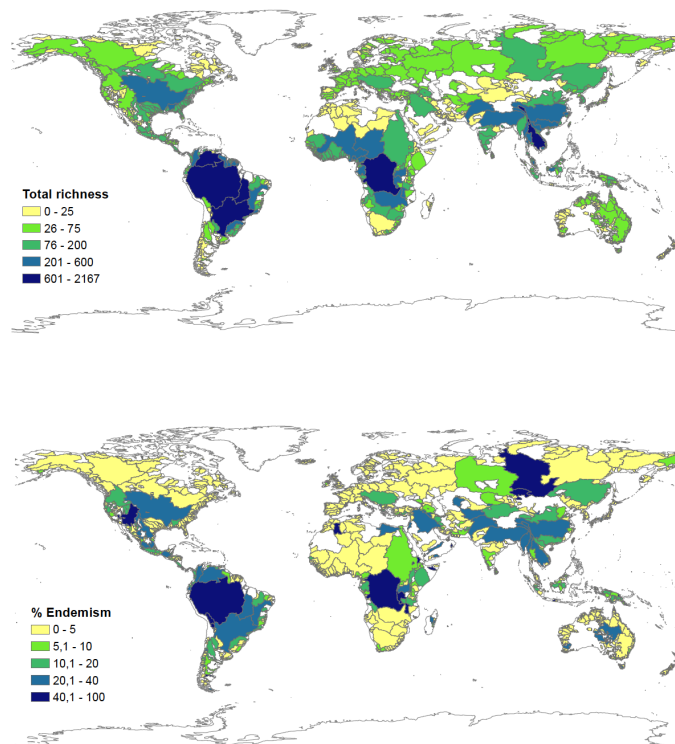
67 Fig. 1. Direct and indirect drivers of biodiversity changes due to human strategy for environmental
 68 control and population expansion (*i.e.* socio-cultural processes). * direct drivers, \$ indirect drivers
 69 through human production of goods and services (*e.g.* infrastructure development, industry, transport).
 70 Circles for energy sources are proportional to their current degree of use. Line arrows indicate direct
 71 links, while dotted arrows indicate feedback effects. Under the proposed scheme two broad interlinked
 72 compartments are responsible for climate and biodiversity changes, *i.e.* the basal energy sources and
 73 the global food system. Both should be tackled jointly to avoid failures in proposing soundful solutions
 74 for climate, biodiversity and human well-being issues, all the more as even if fossil fuel emissions were

75 immediately stopped, current emission trends in global food systems would likely preclude meeting the
76 Paris Agreement goals (Clark *et al.*, 2020).

77 **Current and future threats to freshwater biodiversity and ecosystems**

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

80 Globally, freshwaters cover ~3% of Earth's landmass surface with over 60% of this
81 being permanent water bodies and the remaining being seasonally intermittent (Pekel
82 *et al.*, 2016). Considering flowing waters only, the percentage of intermittency is even
83 greater when analyzing the worldwide river network length (~60%, Messenger *et al.*,
84 2021). Despite their rather marginal representation of the Earth's surface, freshwaters
85 are home to approximately 10% of all described species of fungi, plants,
86 invertebrates, and vertebrates on Earth (Kopf *et al.*, 2015). The relative contribution
87 of freshwater ecosystems to global biodiversity is thus extremely high. As a flagship
88 and well-studied example, species of bony fishes (Actinopterygii) inhabiting rivers
89 and lakes (<1% of Earth's surface) are as numerous as the ones inhabiting the seas
90 (71% of the Earth's surface) (Tedesco *et al.*, 2017a; Dudgeon, 2019) (Figure 2). The
91 natural (physical) fragmentation of habitats and geographic isolation of these systems
92 are most probably involved in explaining this astonishing diversity through positive
93 effects on species speciation rates (Dias *et al.*, 2013; Tedesco *et al.*, 2017b). Indeed,
94 as biological exchange among freshwater water bodies is restricted by terrestrial
95 barriers, freshwater habitats are kind of remote Islands having experienced specific
96 speciation processes (*e.g.* Hugueny *et al.*, 2010; Dudgeon, 2019). As a consequence,
97 freshwater bodies usually display high degrees of taxa endemism (*e.g.* Tisseuil *et al.*,
98 2013).



99
100

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

103 Current major threats to freshwater biodiversity include climate change, habitat
104 modification and pollution from land-use, habitat fragmentation and flow regime
105 homogenization by dams, non-native species, increased eutrophication resulting from
106 nutrient and organic discharges, water abstraction, and over-exploitation (Dudgeon,
107 2019). Those threats currently affect freshwater biodiversity and functioning to
108 varying degrees (Vörösmarty et al., 2010; Dias et al., 2017; Su et al., 2021; Albert et
109 al., 2021) and their additive and potentially synergistic effects will continue to
110 threaten this biodiversity in the future (Knouft and Ficklin, 2017; Carmona et al.,
111 2021). Recognition of this adverse situation has stimulated applied research in
112 developing local grain (e.g. site grain) studies. Results from most of these studies
113 analyzing impact of different stressors on freshwater biodiversity show without
114 ambiguity, but most often difficulties in separating individual effects, that human
115 pressure has disturbed local assemblages globally in their biodiversity (e.g. population
116 decline, local extinctions), structure and functions with habitat loss and alteration,
117 hydrologic modification, water pollution and biological invasions being the major
118 drivers of change (reviewed in Carpenter et al., 2011; Stendera et al., 2012). For
119 example, assessments of 71,494 river sites based on macroinvertebrate assemblages
120 and 37,676 based on fish from 6 continents and 42 nations indicates poor local
121 biological condition of rivers globally. According to this study less than half the sites
122 were in good condition and almost a third were severely impaired (Feio et al.,
123 unpublished results). Results are less straightforward when increasing the grain size
124 (e.g. river basins, lakes, regions) in part because there has been little effort to evaluate
125 effects of anthropogenic factors at these grains and at large extents due to limitations
126 in data availability (Joppa et al., 2016). The few studies performed at these larger
127 grains and at global or continental extents most often conclude that natural
128 geographical factors still dominate over anthropogenic pressures in explaining species
129 richness and community structure, and this for most water bodies and biological
130 models analyzed (e.g. Brucet et al., 2013; Feld et al., 2016). Taking as an example a
131 well-studied biological model (i.e. freshwater fishes), only water pollution (i.e.
132 nutrient enrichment) through eutrophication processes, habitat fragmentation by dams
133 and presence of non-native species have been shown to significantly, although
134 weakly, alter overall biodiversity and the structure and function of communities in
135 lakes (Brucet et al., 2013) and river basins (Blanchet et al., 2010; Villéger et al.,
136 2011; Dias et al., 2017) at continental and/or global extents (but see Su et al., 2021).
137 Worldwide, the greater problem at this time seems thus the loss of freshwater species
138 and the alteration of aquatic community structure and ecosystem functioning at the
139 local grain (Stork, 2010).

140 ***Climate change threats***

141 One of the primary driver underlying patterns of biodiversity on Earth is climate,
142 indirectly acting on speciation, extinction and dispersal processes through “water–
143 energy dynamics” (e.g. Hawkins et al., 2003; Field et al., 2009). Climate and
144 biodiversity are so closely tied that it is not a real surprise that distributions of Earth’s
145 species are changing at accelerating rates with human driven climate change.
146 Scientific evidence is accumulating that many freshwater aquatic species are
147 responding to warming by elevational and/or northward shifts in their distribution
148 ranges, tracking climate warming velocities (Comte et al., 2013; Pecl et al., 2017).
149 However, there are also evidences that species range shifts are idiosyncratic and
150 habitat dependent (Lenoir et al., 2020) and these differential species responses to

151 warming promote and will continue to promote reshuffling of communities and
152 consequent cascading effects on food webs and ecosystem functioning, affecting in
153 fine regional availability of food for humans, particularly in developing countries (e.g.
154 local fisheries, Ojea *et al.*, 2020)

155 Climate change alters freshwater ecosystems and their biodiversity by changing (1)
156 temperatures, (2) water availability and (3) flow regimes through changes in
157 precipitation (Doll and Zhang, 2010; Knouft and Ficklin, 2017) and/or temperature
158 (Blöschl *et al.*, 2017). Increased water temperatures often lead to progressive shifts in
159 the structure and composition of assemblages because of changes in species metabolic
160 rates, body size, migration timing, recruitment, range size and interactions (Parmesan,
161 2006; Scheffers *et al.*, 2016; Pecl *et al.*, 2017; Rosenzweig *et al.*, 2008; Daufresne *et*
162 *al.*, 2009; Myers *et al.*, 2017). There is already evidence of regional and continental
163 shifts in freshwater organism distributions following their thermal niches (Comte *et*
164 *al.*, 2013; Mouton *et al.*, 2022), local extirpations through range contractions at the
165 warm edges of species' ranges (Wiens, 2016), and body size reductions (Daufresne *et*
166 *al.*, 2009). Warmer water temperatures also enhance microorganism metabolism and
167 processing of organic matter (unless dissolved oxygen is limiting), promoting
168 eutrophication when nutrient levels are high (Carpenter *et al.*, 2011; Mantyka-Pringle
169 *et al.*, 2014), and greater omnivory. Warming also induces phenological mismatches
170 between consumers and resources in highly seasonal environments, potentially
171 destabilizing food chain structure (Woodward *et al.*, 2010). Moreover, increase in
172 water temperature and streamflow alterations by climate change may interact with
173 land-use modification to increase autotrophic productivity (Bernhardt *et al.*, 2022) and
174 drive increases in the dominance of species that prefer warm- and slow-water habitats,
175 reorganizing the structure of freshwater communities (Comte *et al.*, 2021). However,
176 evidence shows that conventional anthropogenic factors (listed above) are currently
177 and consistently more important in driving biodiversity threats than the contemporary
178 effects of climate change (Tedesco *et al.*, 2013; Dobson *et al.*, 2021; Caro *et al.*,
179 2022).

180
181 Scenarios of climate change on global freshwater ecosystem biodiversity and
182 functioning were reviewed by Settele *et al.*, (2014). The strongest temperature
183 increases are projected for eastern North America (0.7 to 1.2 °C for RCP2.6 and 8.5
184 for 2050s), Europe (0.8 to 1.2 C), Asia (0.6 to 1.2°C), southern Africa (>2.0°C for
185 RCP8.5) (van Vliet *et al.*, 2016) and Australia
186 ([https://soe.environment.gov.au/theme/built-environment/topic/2016/increased-](https://soe.environment.gov.au/theme/built-environment/topic/2016/increased-extreme-weather-events#table-BLT5)
187 [extreme-weather-events#table-BLT5](https://soe.environment.gov.au/theme/built-environment/topic/2016/increased-extreme-weather-events#table-BLT5)). Moderate water temperature increases
188 (<1.0°C) are predicted for South America and Central Africa (van Vliet *et al.*, 2016).
189 Changes in water temperature are projected to lead to local or regional population
190 extinctions for cold-water species because of range shrinking especially under the
191 RCP 4.5, 6.0 and 8.5 scenarios (Comte and Olden, 2017). Most lowland-tropical
192 freshwater species are expected to tolerate warmer conditions where water is
193 sufficient (Comte and Olden, 2017).

194 Decreased water availability and altered flow regimes reduce habitat size and
195 heterogeneity. This increases population extinction rates because the probability of
196 species extinctions increases with reduced habitat size (Tedesco *et al.*, 2013;
197 Barbarossa *et al.*, 2021). Climate change also alters flow regime seasonality and
198 variability (e.g. Döll and Zhang, 2010; Blöschl *et al.*, 2017) and increases flow
199 intermittency (Pyne and Poff, 2017). This leads to decreased food chain lengths

200 through loss of large-bodied top predators (Sabo *et al.*, 2010), altered nutrient loading
201 and water quality (Woodward *et al.*, 2010), and/or pushing taxa into novel trajectories
202 from which they may not recover (Bogan and Lytle, 2011). However, whatever the
203 RCP scenario, impacts on the timing of seasonal streamflow are found to be generally
204 small (Eisner *et al.*, 2017), minimizing the possible future impact of this driver on
205 freshwater biodiversity. On the other hand, relative to water availability and according
206 to the wet-wetter/dry-dryer mechanism (Held and Soden, 2006; Gudmundsson *et al.*,
207 2017; Wang *et al.*, 2017) more severe water stress in current drylands is expected in
208 the future. Although RCP 2.6 will change water availability distributions little by the
209 end of the 21st century, RCP4.5, 6 and 8.5 scenarios will induce substantial drainage
210 shrinking where semi-arid and Mediterranean climates currently occur. Reduced
211 water availability in those regions, including shifts from permanence to intermittency,
212 will generate population extirpations of all types of freshwater organisms (Jaeger *et*
213 *al.*, 2014), leading to global net biodiversity losses because endemism is usually high
214 in those regions. For example, projected fish extinction rates from drainage shrinking
215 under the SRES A2 scenario (RCP 8.5) in 1010 river basins worldwide show that
216 among the 10% most-altered basins, water availability loss will increase background
217 extinction rates by 18.2 times in 2090 (Tedesco *et al.*, 2013). Also, in glacier-fed
218 high-mountain ecosystems, significant changes to snow and glacier melt regimes,
219 including glacier retreat or disappearance, have already been observed (Leadley *et al.*,
220 2014) and are expected to continue (Kraaijenbrink *et al.*, 2017). This currently, but
221 temporarily, leads to increase the species richness of generalist taxa in glacier-
222 adjacent habitats (positively impacting biodiversity at a regional scale), as well as
223 extinction of endemic « glacier specialist » taxa (negatively impacting total
224 biodiversity at the global scale) (Cauvy-Fraunié and Dangles, 2019).

225

226 ***Land-use and water pollution threats***

227 Land use, especially croplands, mining and urbanization, affect freshwater
228 ecosystems and associated biodiversity through two main pathways. First, water and
229 groundwater withdrawals decrease habitat (water) availability for freshwater
230 organisms leading to increased population extinction rates in rivers and lakes or direct
231 extinctions from riparian zones, wetland, floodplains, and peatland conversions
232 (Gardner *et al.*, 2015; Minayeva *et al.*, 2017), the problem being exacerbated in
233 semiarid regions where water withdrawals lead to some rivers and lakes routinely
234 drying and consequent species extinctions (Foley *et al.*, 2005). Second, water quality
235 is usually degraded by land use. Intensive agriculture increases sediment, nutrient (N-
236 rich fertilizers) and pesticide loads to ground and surface waters (Peñuelas and
237 Sardans, 2022). Urbanization also substantially degrades water quality mostly through
238 organic, pharmaceuticals or phosphorous loadings, especially where wastewater
239 treatment is absent. Mining leads to increased loadings of toxic metals, salts and acids
240 (Johnson and Hallberg, 2005). Such pollutants lead to direct local mortality, impaired
241 individual development and health through bioaccumulation particularly in top
242 predators (Carpenter *et al.*, 2011), finally altering the structure of biological
243 communities (Muturi *et al.*, 2017). Nutrient loadings progressively increase
244 eutrophication, depleting oxygen, killing animals, extirpating submerged macrophytes
245 and producing algal blooms (including toxic varieties of cyanobacteria) (Paerl and
246 Paul, 2012). Pollutants preferentially affect closed systems and estuary biodiversity
247 and functioning (Jenny *et al.*, 2016). For example, urban point sources were the
248 leading cause of hypoxia across European lakes since 1850 (Jenny *et al.*, 2016).

249 Furthermore, deforestation, a key component of land-use change, severely disrupts
250 flooding, thermal regimes, organic matter processing and food web dynamics
251 (Sweeney *et al.*, 2004), exacerbating the establishment and spread of pests and
252 pathogens, especially in tropical regions (Morris *et al.*, 2016). Finally, the loss of
253 lateral hydrological connectivity between rivers and their floodplains through flood-
254 control infrastructures (*e.g.* levees) to satisfy human demand for freshwater and
255 infrastructure development, not only decreases habitat availability but also affects
256 food webs and threatens species that benefit from facultative ontogenetic niche shifts
257 between floodplain and main channel, jeopardizing at the end the entire ecosystem
258 productivity (Opperman *et al.*, 2009; Stoffels *et al.*, 2022).
259 Concerning freshwater habitat, future RCP projections predict an increase (in order of
260 diminishing importance RCPs 2.6, 6, 8.5) or a decrease (RCP 4.5) in cropland area, an
261 increase (RCP 8.5) or a decrease (in order of diminishing importance RCPs 6, 4.5,
262 2.6) in grassland area and an increase (RCPs 4.5, 6) or a decrease (RCPs 2.6, 8.5) of
263 natural vegetation area (van Vuuren *et al.*, 2011), but see Alexander *et al.*, (2017) for
264 slightly different projections. The RCP 4.5 scenario, predicting a decrease of land-use
265 area globally, minimizes future freshwater biodiversity disturbances, followed by
266 RCPs 2.6, 6.0 and 8.5 in decreasing order. However, global scenarios mask
267 continental dissimilarities. For example, projections of future primary vegetation
268 show major decreases in western and middle Asia (scenarios 2.6, 6.0 and 8.5),
269 Australia (only RCP2.6) and North America (only RCP 8.5) (Settele *et al.*, 2014).
270 Concerning water pollution, this anthropogenic pressure has been considerably
271 reduced during the last decades in Australia, North America and Western Europe
272 (Vörösmarty *et al.*, 2010), except for pharmaceuticals, biocides and plastics because
273 of ineffective treatment currently available (Ebele *et al.*, 2017; Wilkinson *et al.*,
274 2022). Reduced water pollution will benefit freshwater biodiversity whatever the
275 scenario. However, Sinha *et al.*, (2017) projected increased eutrophication induced by
276 increased precipitation from climate change in some regions, and Olivier *et al.*, (2017)
277 projected no decrease in nutrient concentrations for most USA lakes despite attempts
278 to reduce diffuse pollution. If there is little technology transfer to developing
279 countries, then water pollution will increase worldwide, particularly in tropical
280 regions because of increased human density notably in Asia and Africa, which is
281 expected to account for over half of global population growth between 2015 and 2050
282 (United Nations, 2015). Under RCP 2.6 if much agricultural, mineral and bioenergy
283 production relocates from high-income to low-income regions, pollution, freshwater
284 biodiversity and aquatic ecosystem functioning will further worsen in those regions
285 (Albert *et al.*, 2021).

286 287 ***Freshwater habitat fragmentation threats***

288 Dams provide the most characteristic example of anthropogenic fragmentation.
289 This stressor alters rivers, floodplain lakes, wetlands and estuaries. Dams transform
290 river basins by creating artificial lakes locally, fragmenting river networks, and
291 greatly distorting natural patterns of sediment transport and seasonal variations in
292 water temperatures and flows (Latrubesse *et al.*, 2017; Flecker *et al.*, 2022). Altered
293 flow seasonality in rivers has led to less diverse fish assemblages, decreased inland
294 fisheries production, less stable bird populations and lower riparian forest production
295 (Jardine *et al.*, 2015; Kingsford *et al.*, 2017; Sabo *et al.*, 2017). Sediment retention by
296 dams leads to delta recession (Luo *et al.*, 2017) and degraded coastal fisheries and
297 tropical mangrove forests. Dams also prevent upstream-downstream movement of

298 freshwater animals and facilitate settlement of non-native species, cause local species
299 extirpations by modifying productivity and increase risk of water-borne diseases in
300 created reservoirs (Poff and Schmidt, 2016). The fragmentation of river corridors by
301 dams also reduces population sizes and gene flows of aquatic species, increasing
302 species extinction risks (Dias *et al.*, 2017; Brauer and Beheregaray, 2020). Dams are
303 mainly concentrated in highly industrialized regions, but future hydropower
304 development will be concentrated in developing countries and emerging economies
305 (Zarfel *et al.*, 2015; Winemiller *et al.*, 2016). Hydropower is expected to expand
306 worldwide whatever the RCP scenario. Most hydropower plants are currently situated
307 in regions where considerable declines in streamflow are projected, resulting in mean
308 reductions in usable hydropower capacity (Turner *et al.*, 2017; Van Vliet *et al.*, 2016).
309 Those regions may increase dam building to compensate for the losses unless other
310 energy options are implemented (Zarfel *et al.*, 2015). Also, population density is
311 continuously increasing and will reach around 10 billion in 2050 (United Nations,
312 2015). This will increase demands for hydropower globally, and especially in tropical
313 regions (Winemiller *et al.*, 2016) where freshwater biodiversity is concentrated
314 (Tisseuil *et al.*, 2013).

315 ***Non-native species introduction threats***

316 Although policies have been implemented to prevent new introductions globally, the
317 increase in numbers of non-native species shows no sign of saturation over time
318 (Seebens *et al.*, 2017). Non-native species may compete with and/or prey upon native
319 species, generating occasional local population extirpations (Carpenter *et al.*, 2011).
320 Non-native species may also alter ecosystem structure and function (*e.g.* Blanchet *et*
321 *al.*, 2010), spread infectious diseases and sometimes may degrade ecosystem services
322 and economies (Leung *et al.*, 2002). They are a key contributor to biotic
323 homogenization of freshwater ecosystems globally (Villéger *et al.*, 2011). Many non-
324 native species are predicted to spread worldwide in the next decades, mainly because
325 of climate change, accelerated economic exchanges among countries, construction of
326 new transportation corridors and increased aquaculture (Seebens *et al.*, 2017).
327 Anthropogenic disturbances (including climate change) coupled with introductions of
328 non-native species have been associated with native species extirpations and/or range
329 reductions in lakes reservoirs and rivers (Bell *et al.*, 2021; Zhang *et al.*, 2022).
330 Because both pressures are expected to continue occurring in the 21st century, further
331 threatening of aquatic species is expected.
332 However, whether non-native species, when introduced, will become invasive (and
333 thus potentially harmful for native communities) or not, is highly context dependent
334 (*e.g.* Manchester and Bullock, 2001).

335

336 ***Intensive harvesting threats***

337 Current estimates of inland fisheries harvest are greatly underestimated (Deines *et al.*,
338 2017), but inland fisheries provide food for billions and livelihood for millions of
339 people worldwide (FAO, 2016), especially in developing countries. Low-income food-
340 deficient countries account for ~80% of the total reported harvest from inland capture
341 fisheries (Lynch *et al.*, 2016). Most global harvesting is concentrated in 16 countries,
342 which have annual inland catches >200,000 tons and together represent 80% of the
343 world total (FAO, 2016). Asian countries represent 63% of global total catches and
344 African nations >13%. Harvests in African and Asian water bodies are already
345 declining, probably because of environmental degradation and overexploitation

346 (FAO, 2016). Given expected human population increases in Africa and Asia,
347 increased harvesting is expected in both continents in the future. Because harvesting
348 decreases population densities and large-bodied species, increased fishing pressure
349 will lead to local extirpations of these species and will alter population (including
350 evolutionary genetic; Czorlich *et al.*, 2022), community structures and food web
351 dynamics (McIntyre *et al.*, 2016). These effects will be magnified by interactions with
352 other anthropogenic stressors, including climate change. Because contributions of
353 inland fisheries to economic security are inversely proportional to development level,
354 rural economies in developing countries will be the most affected.

355

356 **Perspectives**

357

358 As reviewed above, anthropogenic factors and associated processes responsible for
359 the decline of freshwater biodiversity are clearly identified since decades and several
360 existing cost-effective solutions, either technological, nature-based or policy-based,
361 could be applied globally to halt and/or reverse this rapid decline. These solutions can
362 have also benefit for climate change mitigation and human well-being (Pörtner *et al.*,
363 2021; Shin *et al.*, 2022; Smith *et al.*, 2022). Some few examples of potential solutions
364 focusing here on improving water quality and restoring freshwater connectivity are
365 given below.

366

367 ***Improve water quality to sustain aquatic life***

368

369 Options include:

370 (1) Improving wastewater treatment technologies and water reuse to reduce pollution
371 from domestic and industrial point sources as well as maintaining sustainable water
372 resources (*e.g.* Bailone *et al.*, 2022); (2) Improving urban development and
373 agricultural practices by stopping wetlands and peatlands conversion for urban
374 development and agriculture expansion and favoring maintenance of riparian zones at
375 the periphery of all water bodies. Indeed, wetlands, peatlands and rivers riparian
376 zones act as buffer areas able to improve the chemical and biological quality of water
377 through filtering nutrients and stopping erosion and consequent sediment loadings
378 (*e.g.* Engle, 2011); (3) Reducing the use of nutrients (nitrogen and phosphorous),
379 pesticides, herbicides and fungicides applied to land as fertilizers or pest management
380 and improving livestock systems and aquaculture practices by reducing the use of
381 veterinary medicines (antibiotics and growth hormones), which move from lands
382 through freshwater ecosystems. For example, water pollution from nutrients (*e.g.*
383 leading to ecosystem eutrophication and consequent hypoxia) occurs when fertilizers
384 are applied at a greater rate than they are fixed by soil particles or exported from the
385 soil profile by plant uptake. Optimizing nutrient inputs to satisfy plant uptake only
386 should strongly minimize the export of nutrients to freshwaters and associated
387 environmental and biological impacts. In a same way, manure from livestock
388 production should be stored and treated (*e.g.* through anaerobic fermentation), which
389 can produce organic fertilizers and soil conditioners, decreasing at the same time the
390 need for chemical fertilizers; (4) Favoring efficient and well-managed crop irrigation
391 schemes (*e.g.* drip irrigation, Grafton *et al.*, 2018) which can, besides decreasing the
392 amount of water withdrawal, reduce water return flows and therefore the migration of
393 fertilizers and pesticides to adjacent water bodies.

394

395 ***Safeguard and restore freshwater connectivity***

396

397 Hydropower is a leading component of current and future renewable energy
398 portfolios in many countries worldwide and construction of large dams is booming
399 in many countries (Zarfl *et al.*, 2015; Winemiller *et al.*, 2016).

400 Several solutions exist for reducing the loss of functional connectivity for riverine
401 communities due to dam infrastructures. Some are listed below: (1) Strategic siting of
402 new infrastructures can be made by using multi-objective optimization frameworks to
403 identify least impactful projects by balancing, for example, connectivity maintenance
404 with hydropower generation (*e.g.* Flecker *et al.*, 2022); (2) New technical solutions
405 for hydropower dams, such as in-stream turbines, can be privileged to maintain the
406 fluvial system connectivity (Chaudhari *et al.*, 2021);(3) Systematically designing
407 technical solutions (*e.g.* fish pass) to maintain the fluvial system connectivity for
408 aquatic biota for dams of all sizes (Albert *et al.*, 2021); (4) Systematic dam removal
409 can be considered in regions with aging dams render them unsafe or economically not
410 viable (Foley *et al.*, 2017). However, hydropower dams represent only a small
411 fraction of artificial barriers disrupting riverine system connectivity, small instream
412 infrastructures such as weirs, culverts and fords actually constituting the main cause of
413 connectivity loss (*e.g.* Belletti *et al.*, 2020). Many of these small barriers are old and
414 obsolete and can thus be removed to restore connectivity, without major technical
415 difficulties nor strong expected conflict between local stakeholders (but see Blanchet
416 and Tedesco, 2021).

417

418 ***Expand the network of protected areas***

419

420 Protected areas (PAs) play a fundamental role in conserving genetic, species
421 and ecosystem diversity, and in ensuring delivery of ecosystem services from natural
422 habitats. Currently around 17% of global inland surface waters are covered by PAs
423 (Bastin *et al.*, 2019), which is in phase with the Strategic Plan for Biodiversity of the
424 Convention on Biological Diversity (CBD), to conserve by 2020 at least 17% of
425 terrestrial and inland water areas. However, current protected areas are far from being
426 geographically uniform (Bastin *et al.*, 2019) and recent proposals converge around
427 protecting 30 per cent of inland water areas by 2030, with appropriate prioritization
428 (*i.e.* geographical and ecological representability, and connectivity) and management
429 improved (<https://www.cbd.int/article/draft-1-global-biodiversity-framework>). As
430 protected areas are most often essentially terrestrially defined, protected area
431 networks are also not fully appropriate for managing freshwater ecosystems (*e.g.* Leal
432 *et al.*, 2020) so that it will be important to design these protected areas for the
433 particular spatial and temporal complexities of freshwater ecosystems (Albert *et al.*,
434 2021).

435

436

437

438

439 **Conclusion**

440

441 The selected potential solutions listed above, most of them well-known since a
442 long time, are easy to implement and several recovery plans and management Agenda
443 to halt and reverse the rapid decline of biodiversity have been recently proposed (*e.g.*
444 Tickner *et al.*, 2020; Van Rees *et al.*, 2021; Maasri *et al.*, 2022) but success will
445 require systemic changes across public policy. These changes are far from being

446 insurmountable if there is a sufficient political will to do so. In the same way as for
447 climate change, decision makers need to move urgently beyond well-intentioned
448 speeches as it is now time for decisive action.
449

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452 (2019) and of the IPBES-IPCC co-sponsored workshop (2020), the views expressed
453 here represent the individual views of the author.
454

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