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# Freshwater biodiversity impacts of global hydropower dams

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Hydropower expansion creates tension between renewable energy goals and freshwater ecosystem health. However, the global impacts of dams across the full spectrum of freshwater biodiversity remain poorly quantified. Here, we combine remote sensing and global threatened species datasets to assess dam-related risk patterns for fish, mollusks, mammals, odonates, and amphibians. We show that threatened freshwater species are consistently more common near dams than elsewhere, with mammals showing the highest exposure. Most species whose risk status changed between 1996 and 2022 shifted toward higher threat levels in dam-influenced areas affected by habitat loss and reduced river connectivity. Planned future dams, concentrated in Global South countries, may further elevate extinction risk, particularly for critically endangered fish. These findings support sustainable planning that balances energy development with freshwater conservation.

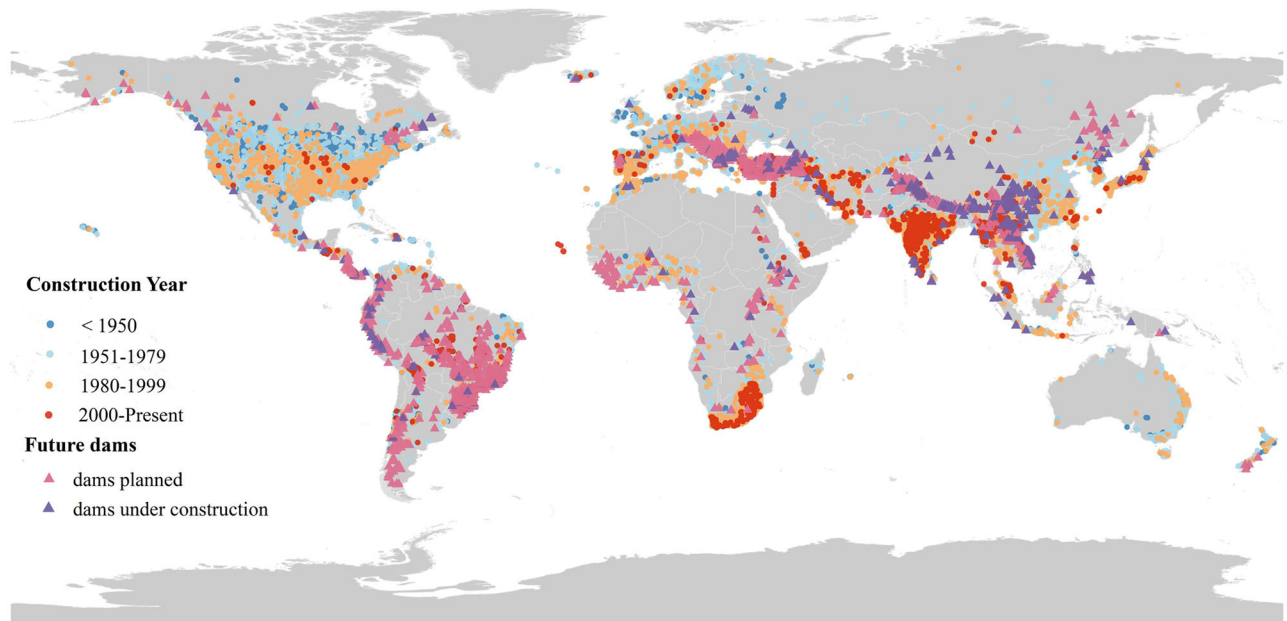
Dams have played an essential role in meeting social needs and economic development since ancient times<sup>1,2</sup>, providing a variety of essential services, such as power generation, flood control, crop irrigation, water supply, and navigation. In the latest effort to develop a carbon-neutral society while meeting demand for rapid economic development<sup>3</sup>, hydro-dams have become increasingly important for renewable energy generation and water resource management<sup>4</sup>. Hydropower is a critical source of low-carbon energy<sup>5,6</sup>, reducing global emissions by approximately 2.8 billion tonnes of carbon dioxide equivalent annually<sup>7</sup>. This positions dams as a cornerstone in achieving the goal of universal access to affordable clean energy (SDG7)<sup>8</sup>.

As a result, global dam construction has considerably accelerated since the 1950s, reaching a peak in the latter half of the 20th century<sup>9</sup>. Much of this expansion occurred in North America, Europe, and Oceania during this period, while growth in the 21st century has increasingly shifted toward the global south<sup>10</sup> (Fig. 1). Currently, there are approximately 58,000 large dams worldwide (with heights exceeding 15 meters)<sup>11</sup>, making a combined reservoir capacity between 7000 and 8300 km<sup>3</sup>. According to the 2021 report from the International Energy Agency, hydropower accounted for approximately 16% of the global electricity generation and over 72% of all

renewable power<sup>12</sup>. As hydropower emerges as a key renewable energy source and a pivotal part of new energy frameworks, the expansion of hydropower dams is being actively promoted in national development plans<sup>13</sup>. For instance, at least 3700 large dams are currently under construction or proposed across the globe<sup>14</sup>, primarily concentrated in less economically developed areas like Africa, South America, Southeast Asia, and Central Asia (Fig. 1).

Although hydropower development generates socioeconomic benefits, it can also inflict environmental impacts<sup>15</sup>. The change to river systems by hydro-dams creates profound impacts on freshwater ecosystems and aquatic community structures<sup>16,17</sup>. Indeed, while freshwater accounts for a mere 0.01% of the world's total water storage, it provides habitats for around 100,000 species, over 6% of all known species<sup>18</sup>. The effects of dams on rivers are primarily reflected in the disconnection of river systems<sup>19</sup>, leading to blocked migration routes for aquatic species<sup>15,20</sup>, water pollution, and habitat destruction<sup>21</sup>. In addition, they alter river flow and temperature, adversely affecting native species, and significantly reduce sediment transport, harming migratory species in rivers, estuaries, and oceans<sup>22</sup>. Hence, damming waterways can trigger substantial changes in freshwater biodiversity,

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**Fig. 1 | Global distribution of dams.** Existing dams (circles) are categorized by construction era, while triangles represent future projects, distinguishing between dams that are planned and those currently under construction.

stimulating cascading effects on a variety of essential ecological services within the biosphere<sup>15,23</sup>.

Previous studies have largely concentrated on hydrological alterations, thermal regimes, sediment trapping, and river fragmentation, with many assessments conducted at the scale of individual dams or river basins<sup>24–28</sup>. This body of work has substantially advanced our understanding of how dams modify flow and connectivity. Moreover, recent site-specific studies have comprehensively assessed impacts on habitat quality and aquatic community structures<sup>24,29</sup>. However, research at the global scale remains limited in scope. Existing global assessments have predominantly focused on specific taxonomic groups (particularly fish and freshwater megafauna) or have relied on river-network fragmentation as a primary indicator of biodiversity risk<sup>30–32</sup>. Taken together, the existing literature demonstrates the value of spatially explicit analyses for evaluating dam impacts, but also highlights that current applications remain uneven across taxa and scales.

In addition, the ecological footprint of hydropower dams extends beyond the river channel<sup>33</sup>. Reservoir inundation and associated infrastructure, such as roads and transmission lines, can drive extensive forest loss and fragmentation in surrounding terrestrial and riparian landscapes<sup>33–37</sup>. Previous studies have established the validity of utilizing spatial overlay analyses (e.g., concentric buffer zones) to quantify these lateral impacts, particularly regarding land-use patterns and habitat loss<sup>38,39</sup>. However, current applications of this spatially explicit method in freshwater biodiversity conservation have been largely restricted to single taxonomic groups, primarily fish, or have relied on coarser watershed scales<sup>14</sup>. Consequently, there remains a need for more comprehensive assessments that consider a broader spectrum of freshwater taxa in order to fully characterize localized extinction risks.

Proposed future dams, concentrated in the global south regions, have been studied through scenario modeling to assess their effects on local economies and river connectivity. These approaches typically employ strategic portfolio planning to optimize trade-offs, aiming to reconcile hydropower expansion with the maintenance of river connectivity and sediment dynamics, thereby attempting to mitigate the ecological footprint of infrastructure development<sup>40</sup>. While these strategic planning frameworks effectively address hydrological trade-offs, the quantification of potential risks to specific endangered species has received comparatively less attention. In particular, further quantitative analysis is needed to fully understand

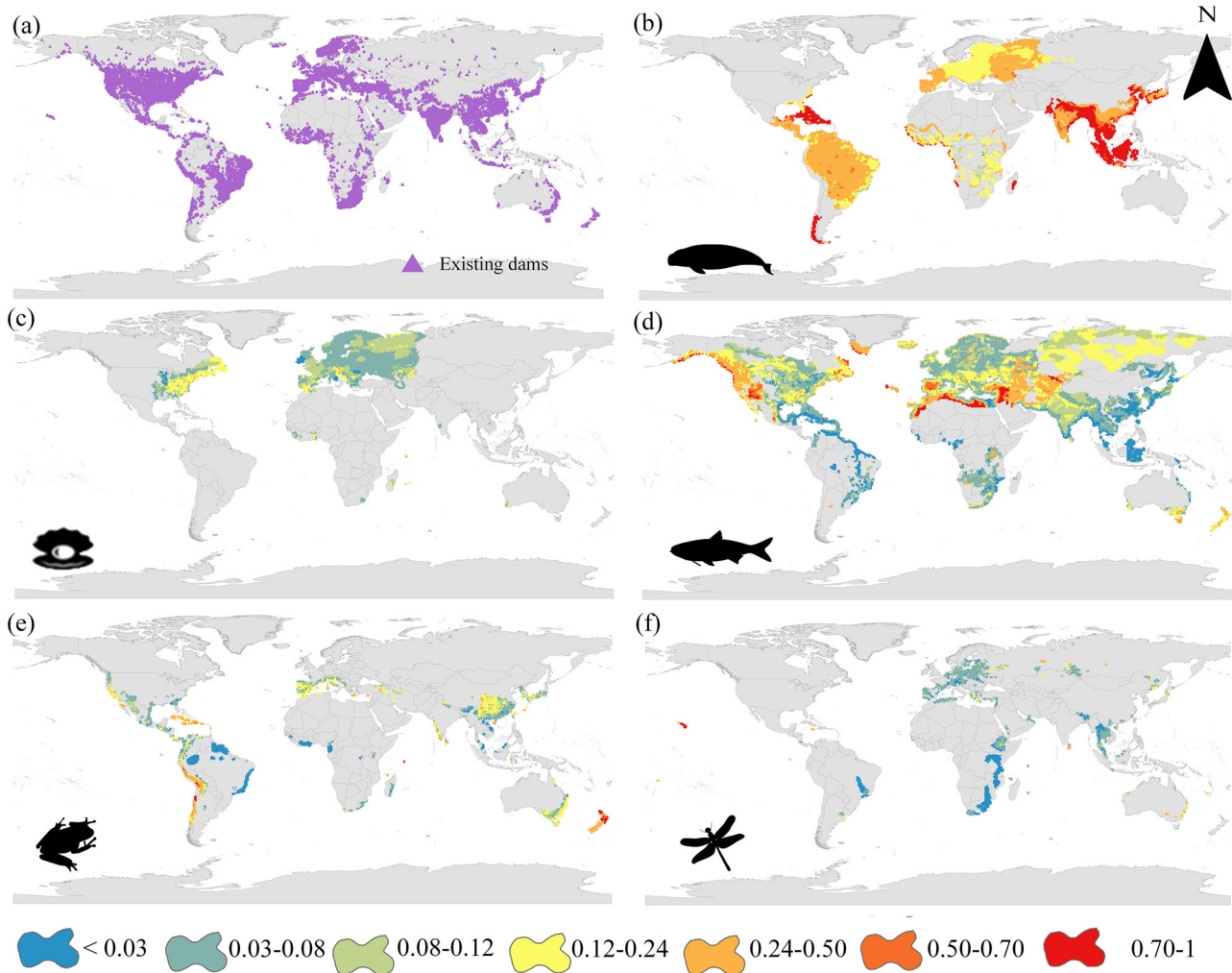
how future dams might interact with critical habitats and influence the temporal dynamics of extinction risk. Moreover, few studies have systematically compared dams of different sizes or evaluated how proposed future dams may amplify risks in already vulnerable regions. These research gaps underscore the urgent need for a global, comprehensive, and multi-scale assessment to better understand the long-term and future effects of dams on freshwater biodiversity.

Rapid advancements in remote sensing have provided the tools to quantitatively assess the global footprint of hydropower dams on freshwater biodiversity<sup>41</sup>. Building on this foundation, our study leveraged the latest global dam tracker (GDAT)<sup>10</sup> alongside high-resolution river connectivity data<sup>42</sup> to investigate the environmental and biodiversity impacts of existing and planned dams. In particular, we aimed to: (1) examine the richness and threat levels of freshwater species within dam-affected areas globally; (2) assess the potential spatiotemporal impacts of existing dams of varying sizes on freshwater biodiversity and their underlying drivers; and (3) evaluate the relationships between proposed future dams and national economic development while projecting their potential biodiversity consequences. These analyses highlight both historical and prospective interactions between dams and freshwater ecosystems, aiding in balancing water resource development with biodiversity conservation.

## Results

### Spatial distribution of endangered species within dam influential areas

The conservation status of all freshwater species within the dam influential areas was systematically assessed, encompassing five primary categories: Odonata (dragonflies and damselflies), freshwater mammals, freshwater mollusks, freshwater fish, and amphibians. A total of 14,260 species were identified, including 3269 kinds of amphibians, 7117 fishes, 114 mammals, 1541 mollusks, and 2219 Odonata (Table S1). We found over 3213 threatened species (CR, EN, and VU) among all, representing 23% of the entire assemblage (Fig. S1). Among all the freshwater species assessed, mammals exhibited the most pronounced endangerment, with a threat proportion of 38.6%. This was followed by mollusks and fish, with threat levels being at 34.1% and 23.6%, respectively. Notably, despite the proportion of threatened freshwater fish species in the region of dam influence being less than 24%, their absolute count at 1679 species was the highest across all evaluated categories (Table S1).



**Fig. 2 | The proportions of threatened freshwater species across different categories in dam areas. a** Global distribution of existing dams. Proportions of threatened species across five taxonomic groups: **b** freshwater mammals, **c** freshwater

mollusks, **d** freshwater fish, **e** amphibians, **f** Odonata. The color gradient indicates the ratio of threatened species to total species richness, ranging from low (blue) to high (red). (Animal silhouettes are sourced from Phylopic.org).

Utilizing the spatial distribution data of species from the IUCN Red List, we calculated the richness of freshwater species in the dam areas and subsequently created maps illustrating the proportion of threatened species (CR, EN, and VU) in different categories (Fig. 2). We found freshwater mammals had the highest proportion of threat across most parts of the world. For example, threatened mammals ranged between 24 and 50% in South America (Fig. 2b). This proportion was even higher in the dam regions of Southeast Asia, which, as one of the richest biodiversity spots in the world, had over 70% of freshwater mammals experiencing threats. Both of the two regions own many important long rivers, such as the Amazon and the Mekong rivers, where numerous dams have been built, and more are coming.

Freshwater mollusks in dam areas were predominantly found in North America and Europe, of which the high threats were located in the river systems of southeastern North America, like the Mississippi and in Western Europe’s Danube, ranging from 10 to 30% (Fig. 2c). We found fish were the most broadly affected freshwater species by the dam construction, which experienced threats in all dam areas across the globe (Fig. 2d). For instance, the southern Nile basin in East Africa had over 18 threatened fish species, bearing the highest number among all global basins.

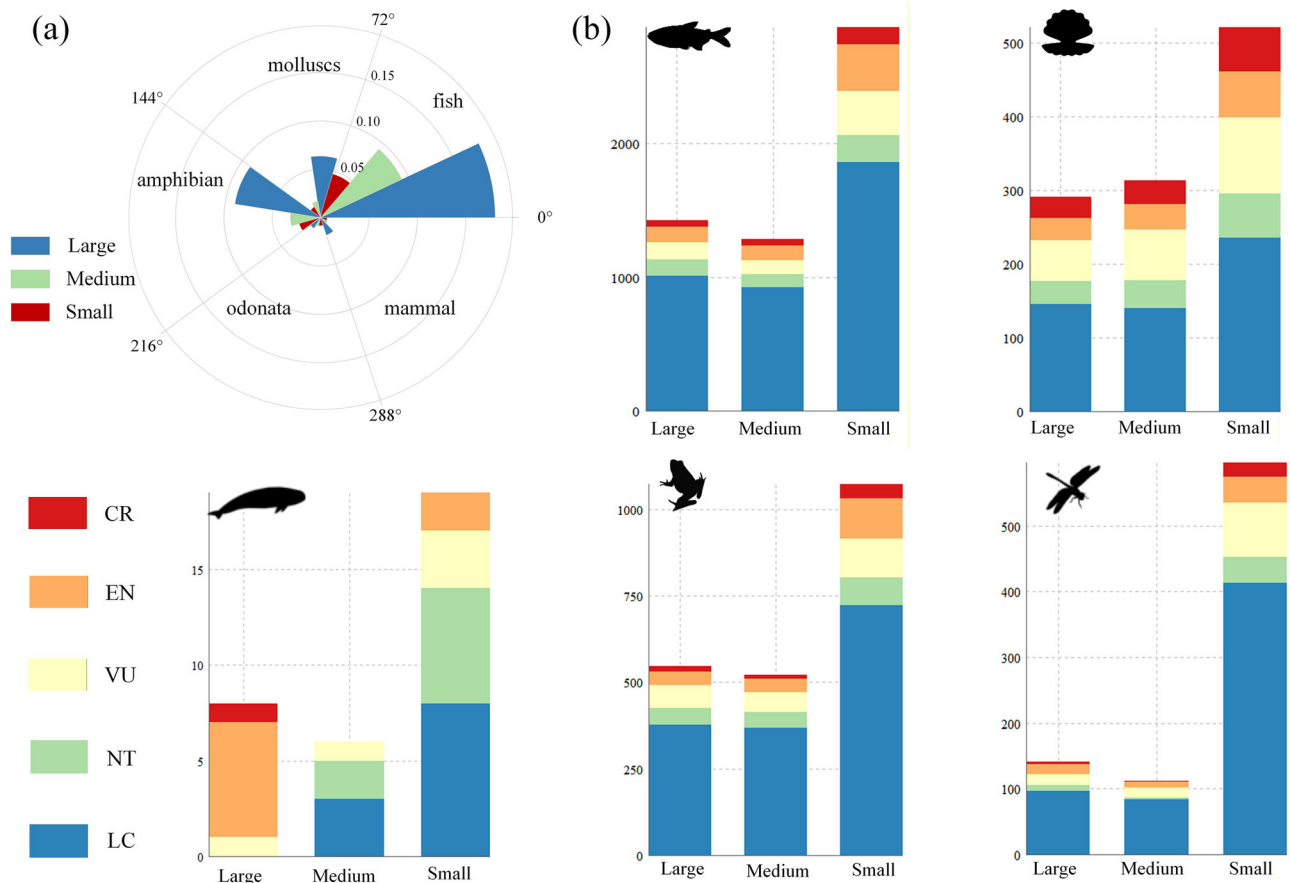
In addition, rivers in western North America and western Asia that are densely dammed showed a high proportion of threatened species, ranging from 25 to 50%. Notably, amphibians, which require specific freshwater and forest habitats, exhibited the highest threat proportion near the Amazon

River in western South America, exceeding 50%. This was followed by the Yangtze River basin in China, with a threat ratio of around 25% (Fig. 2e). Compared to other groups, Odonata (dragonflies and damselflies) appeared less affected by dams, exhibiting low threat ratios that were primarily distributed in southeastern Africa and northwestern Europe (Fig. 2f).

**Impacts of dam sizes on surrounding environments and freshwater species**

The analysis indicates that the spatial overlap with critical habitats varies among dams of different sizes. Larger dams tend to have a greater area of critical habitat located within their buffer zones. Large dams, though relatively few in number, have the largest overlap area, averaging 509,558 km<sup>2</sup>, more than twice that of small dams (Table S2). Their minimum overlapping area, at 12,768 km<sup>2</sup>, is 3.5 times greater than that of small dams (Table S2). While small dams individually have a smaller overlap area, their cumulative spatial extents become pronounced due to their large numbers and extensive distribution. Medium-sized dams exhibit overlap areas that are intermediate between those of large and small dams. Therefore, the planning and construction of large dams necessitate stricter environmental impact assessments and regulatory measures to mitigate potential risks in these high-overlap regions.

The impact of large, medium, and small dams on threatened species was assessed separately using the intersection method. Globally, on a per-dam basis, large dams consistently impacted more species across five



**Fig. 3 | Differential impacts of dam sizes on threatened and endemic freshwater species.** **a** Average number of threatened species affected per dam across five taxonomic groups, categorized by dam size (large, medium, small). **b** Total number

of endemic species affected by dams of different sizes, broken down by IUCN Red List categories (CR, EN, VU, NT, and LC). (Animal silhouettes are sourced from Phylopic.org).

categories of freshwater species compared to medium or small dams (Fig. 3a). This effect was particularly pronounced for freshwater fish, amphibians, and mollusks, where large dams exerted the highest average impact. In contrast, the differences in impact by dam size were minimal for dragonflies and mammals.

The impact of dams of varying sizes on endemic species was also investigated (Fig. 3b). Our findings revealed that small dams, widely distributed across global regions, had a greater overall impact on endemic species compared to medium and large dams. The number of species impacted by small dams exceeded those of large and medium dams by more than twofold. Additionally, the proportion of threatened endemic species affected by small dams was higher compared to medium and large dams. This trend was particularly evident among endemic species in Odonata and mammals.

### Temporal changes in extinction risk of species associated with dam impacts

The temporal changes in extinction risk of freshwater species within dam-affected areas were assessed from 1996 to 2022 (Fig. 4). Our results showed that a large number of freshwater species remained unchanged during the 26 years of study time. Among species whose conservation status did change, more than 85% shifted to higher threat categories, whereas fewer than 15% showed improvements (Fig. 4a).

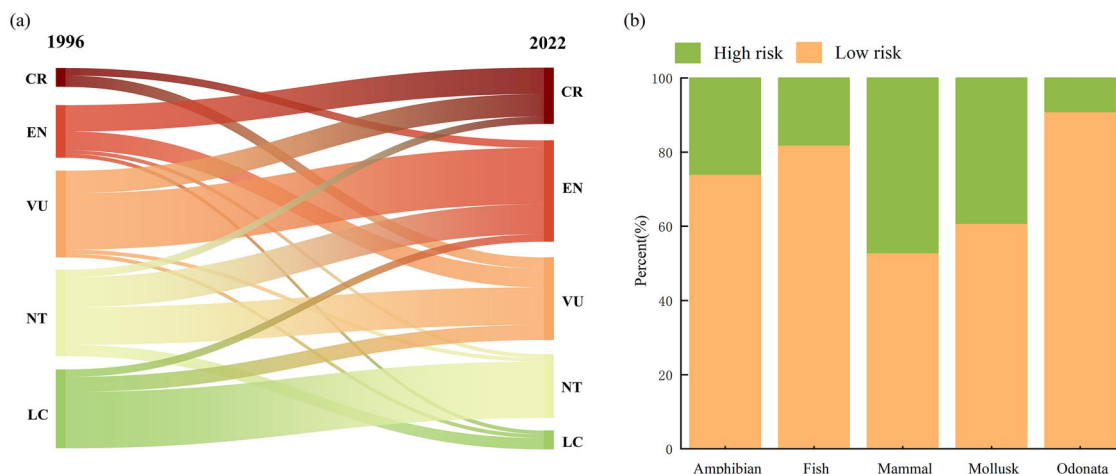
Among these species with altered risk levels, amphibians exhibited the most considerable change, with approximately 46 species affected, followed by fish with 21 species (Table S3). According to our high-versus low-risk classification, larger-bodied freshwater mammals (e.g., the Irrawaddy

dolphin and *Platanista gangetica*) exhibited the highest proportion of high-risk outcomes (47%), followed by freshwater mollusks (39.3%) (Fig. 4b).

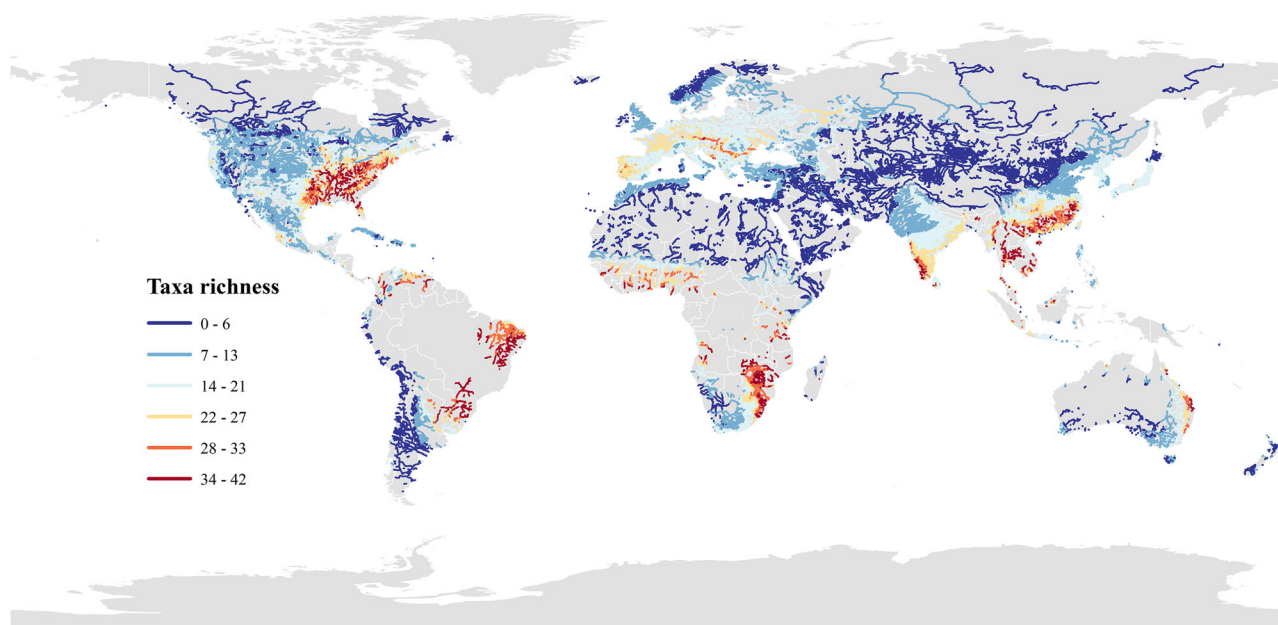
### Overlap of dams with changes in riverine environments

The connectivity of total 70,000 global rivers at various lengths with constructed dams was assessed, ranging from less than 10 km to over 1000 km. Our analysis revealed that North America and Asia bear the greatest number of non-free-flowing rivers (NFFRs) (>10 km) in the world (Table S4). This pattern reflects the cumulative impacts of widespread dam construction across all size classes. Notably, according to the International Commission on Large Dams, these continents were also the epicenters of intensive dam construction in the last century. In contrast, regions such as the Amazon Basin and the Orinoco basin in South America, as well as the Congo basin in Africa, currently possess a multitude of free-flowing rivers (Table S4).

Our analysis of freshwater species in NFFRs exceeding 10 km in length revealed that over 70% of endangered species among the five selected freshwater taxa inhabit in these rivers, with particularly high proportions observed for freshwater mammals, dragonflies, and fish (Table S5). Examination of population trends indicated that most of these species are experiencing declines, with over 50% of freshwater mammals, amphibians, and dragonflies classified as having a current “decreasing” population trend according to IUCN (Table S6 and Fig. S2). Hotspots of non-free-flowing river impacts were identified using our species richness map of dam-fragmented rivers (Fig. 5). The analysis revealed that the eastern Mississippi River Basin in North America, the Mekong River Basin in Southeast Asia, the Zambezi river in southern Africa, and the middle and lower reaches of



**Fig. 4 | Temporal dynamics of extinction risk for freshwater species in the vicinity of dams (1996–2022).** **a** Sankey diagram illustrating the transitions of species between IUCN Red List categories over the study period. The flow width is proportional to the number of species. **b** Proportion of species undergoing high-risk versus low-risk transitions across five freshwater taxonomic groups.



**Fig. 5 | Global distribution of threatened freshwater taxa richness within non-free-flowing rivers (NFFRs).** The map illustrates fragmented river segments (>10 km) based on the cumulative richness of threatened species across five major taxonomic groups: freshwater fish, mollusks, amphibians, mammals, and odonates. Warmer colors (orange to dark red) indicate biodiversity hotspots with high concentrations of threatened species exposed to reduced river connectivity.

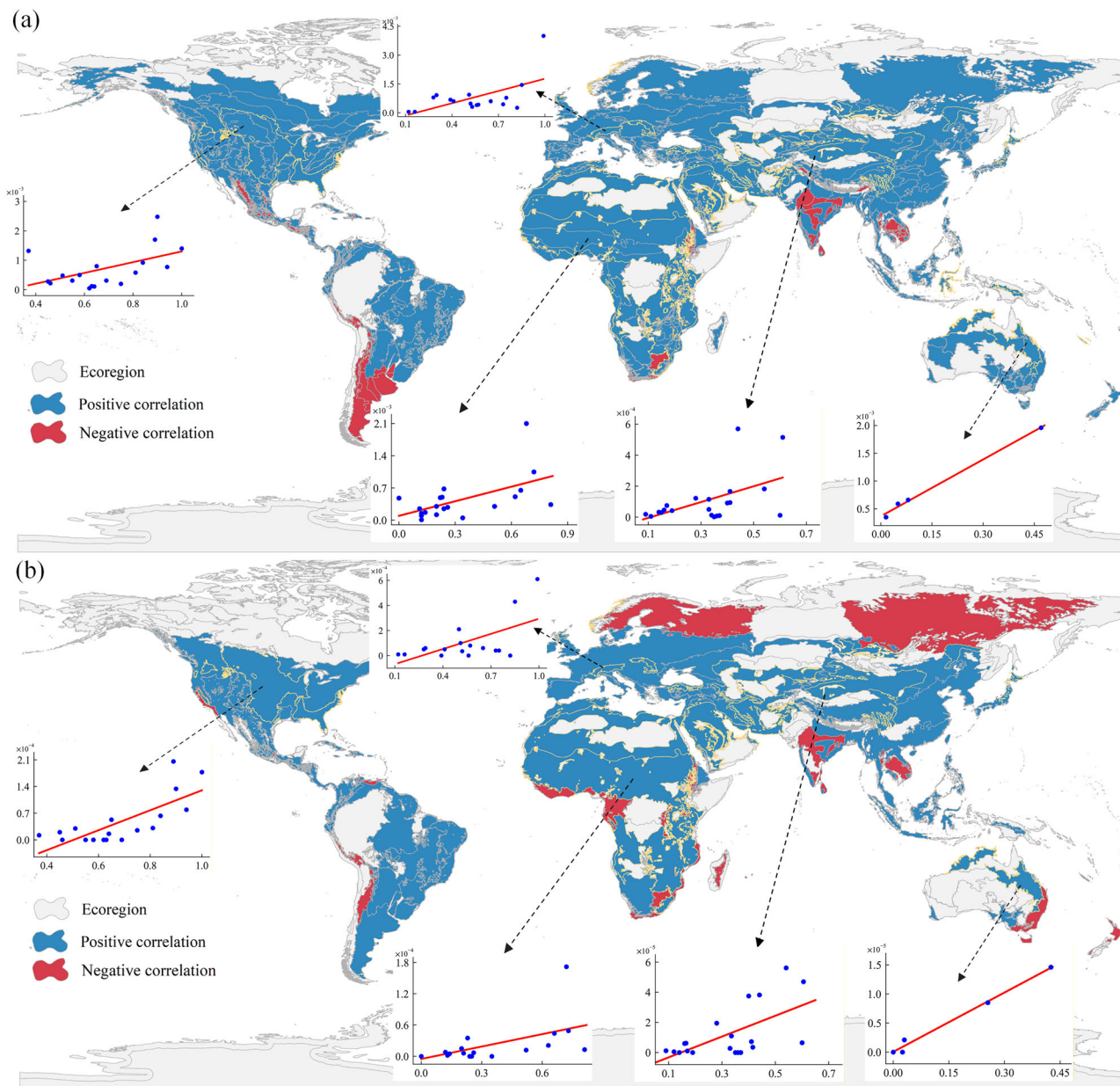
the Yangtze River Basin in China host a high concentration of threatened freshwater species.

In our comparative analysis within each of the 56 bio-realms containing dams worldwide, we found that the proportion of NFFRs is generally positively associated with the degree of freshwater biodiversity threat (Fig. 6a). Specifically, 31 bio-realms exhibited a positive correlation, with about one-third of these results being statistically significant changes ( $p < 0.05$ ), and the relationship was particularly robust in regions with larger sample sizes, underscoring the pervasive negative impacts of dams on freshwater biodiversity. By contrast, only 9 bio-realms showed negative correlations, most of which were not statistically significant, a pattern that may reflect limited sample sizes, data uncertainties, or the establishment of protected areas. For instance, in the Western Ghats of India, although dams initially had negative ecological effects, some reservoirs were later incorporated into protected areas, which, in current assessments, appear to show “positive effects”. Further analyses revealed a similar pattern between the

proportion of NFFRs and species population declines (Fig. 6b), with 25 bio-realms showing positive correlations, 15 showing negative correlations, and the remainder displaying no clear trend. Notably, more than 90% of statistically significant cases were positive, and the association was especially robust in bio-realms with larger sample sizes ( $N \geq 10$ ), indicating a consistent and significant link between disrupted river connectivity and species population declines.

**Overlap of dams with habitat types**

A large number of dams have been built in the important biodiversity habitats (Fig. 7a). We found 6240 dams, which make up 18% of the total existing dams, are situated within natural habitats (Fig. 7b), with 32% of these dams primarily intended for hydroelectricity generation. In contrast, dams built in natural habitats for irrigation merely accounted for 8% (Fig. 7c). However, within the global dam assessment tool (GDAT) database, the most prevalent primary purposes of dams were both irrigation and



**Fig. 6 | Correlations between the proportion of non-free-flowing rivers and biodiversity indicators across ecoregions. a** Density of threatened species (unit: count/km<sup>2</sup>); **b** density of declining threatened species (unit: count/km<sup>2</sup>). Blue regions indicate a positive correlation (higher fragmentation associated with higher

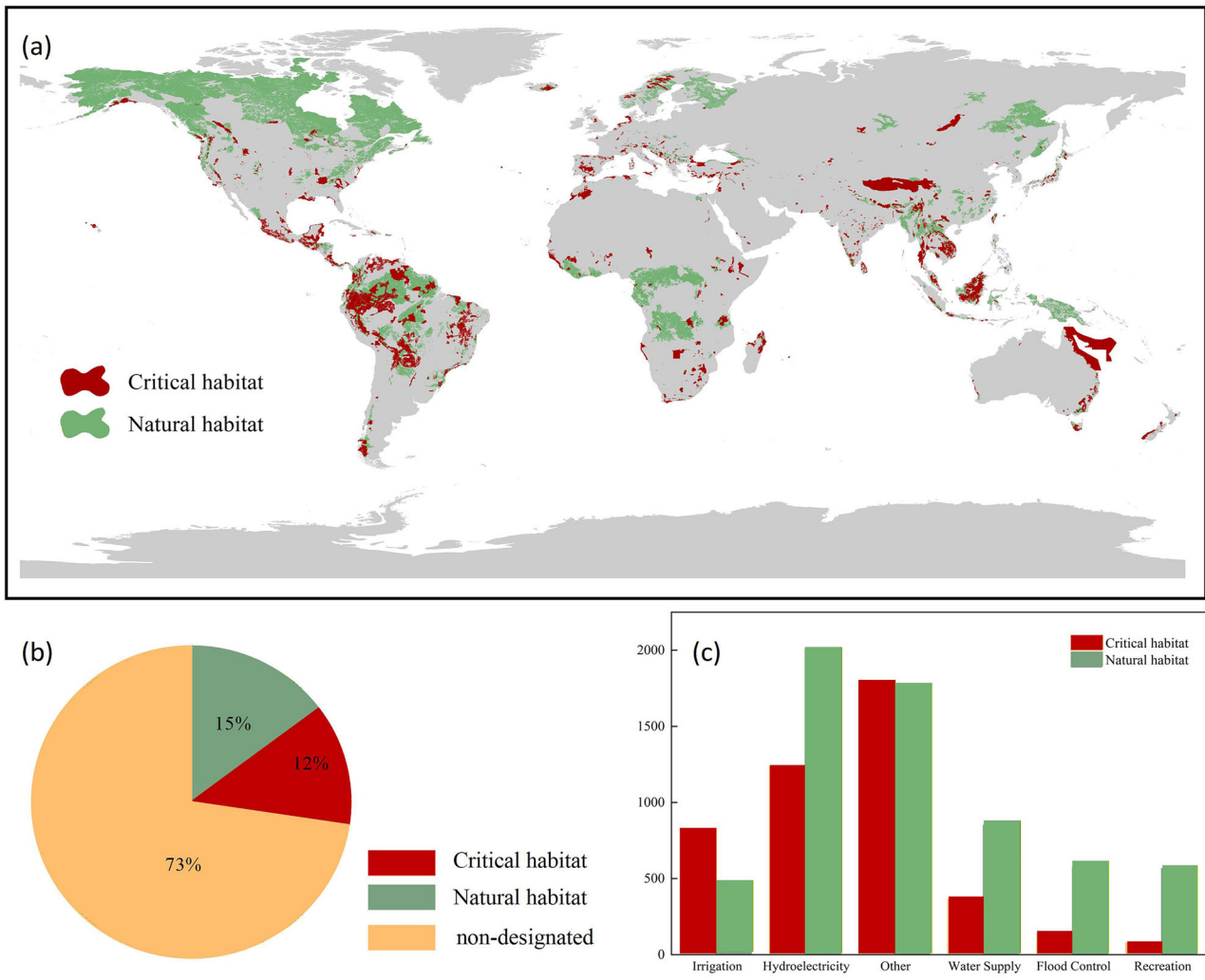
threat density), while red regions indicate a negative correlation. Insets show scatterplots for ecoregions in which the correlations are statistically significant (X: proportion of non-free-flowing rivers; Y: corresponding biodiversity indicator).

hydroelectricity, corresponding to 25% and 20% of the total, respectively. This discrepancy might be because hydroelectricity dams typically require more varied topography and tend to be located in more remote areas, while irrigation dams are usually situated close to farmland. Consequently, the overlaps between areas suitable for hydroelectricity dams and natural habitats would be much more than those for irrigation dams.

Similarly, for the 4432 dams (13% of total existing dams) constructed in critical habitat (Fig. 7a), of which 28% were used for hydroelectricity and 18% for irrigation. The increase in the proportion of irrigation dams may be due to the locations of the critical habitats, in which the species tend to be close to and heavily affected by the human settlements (Fig. 7c). The operation of dams within habitats inevitably involves the clearing and flooding of vast tracts of land and vegetation, and the water storage in reservoirs alters flow velocity and temperature. Such changes may lead to the loss of biodiversity and the degradation of wetland and riverine ecosystems.

### The future dams proposed in ecologically important habitats

Among the 2989 dams scheduled for construction, 1049 (38%) are to be located within natural habitats, and 827 (32%) within critical habitats (Fig. S3a). Compared to current dams, a larger proportion of future dams are proposed within habitats that hold high ecological values. Based on the minimum buffer zone, the area of critical habitats impacted by dams in Asia is the largest, totaling 1035.5 km<sup>2</sup>, followed by South America with an area of 490.4 km<sup>2</sup> (Table 1). For natural habitats, South America and Asia possess influential areas of 1176.1 and 881.4 km<sup>2</sup>, respectively. Based on the maximum buffer zone, Asia exhibits the largest area of critical habitats affected, amounting to 34,021.8 km<sup>2</sup>, with the area of natural habitats also being the greatest at 46,699.1 km<sup>2</sup> (Table 1). More importantly, the majority of these habitats to be affected by dams are in the Southeast Asian areas where the hottest biodiversity spots are located. In addition, we found a high proportion of



**Fig. 7 | Overlap of existing dams with global biodiversity habitats.** **a** Spatial distribution of critical and natural habitats intersected by dam locations. **b** Proportion of total dams situated within critical habitats, natural habitats, and non-designated areas. **c** Primary purposes of dams within habitat areas.

**Table 1 | The areas of critical and natural habitats within the minimum, medium, and maximum buffer zones of dams across global continents**

CONTINENT	Critical habitat (km <sup>2</sup> )			Natural habitat (km <sup>2</sup> )		
	Min	Med	Max	Min	Med	Max
South America	114.0	345.0	3845.8	214.0	3613.4	7997.9
Asia	1035.5	3159.0	34021.8	881.4	3114.8	46699.1
Europe	323.5	981.7	8840.9	453.9	1534.2	17151.3
North America	490.4	1515.4	17614.4	662.6	1176.1	42949.2
Africa	78.1	238.1	2977.9	88.7	275.5	4101.5
Oceania	11.0	26.1	106.9	0.7	1.4	62.7

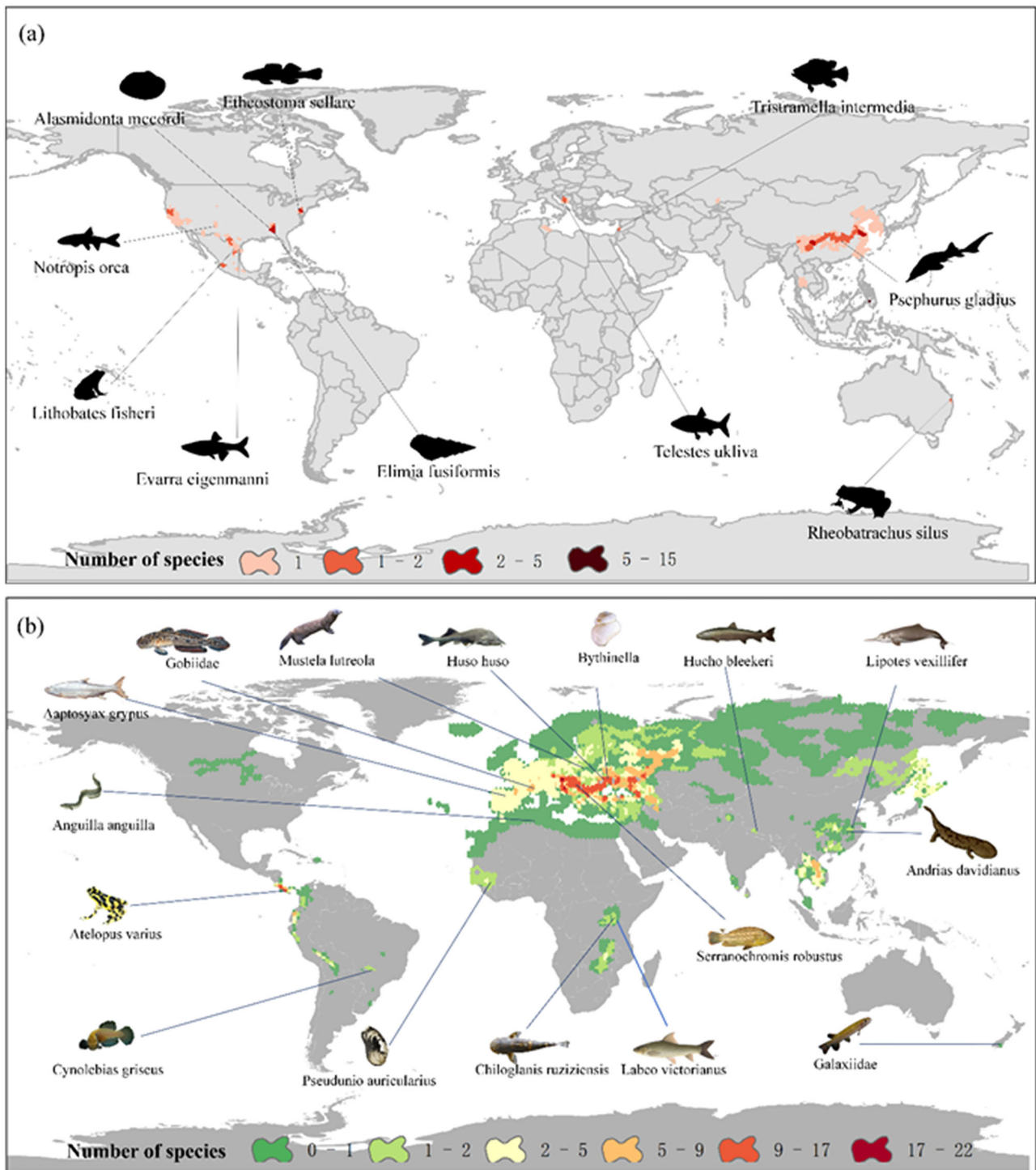
threatened species within the potential impacted areas of future planned dams, including 34 species (37%) of freshwater mammals, 313 species (14%) of amphibians, 151 species (19%) of freshwater mollusks, and 622 species (13.4%) of freshwater fish (Fig. S3b). In addition, our findings indicate that over 80% of future dams are planned on highly free-flowing rivers, which will reduce river connectivity and inevitably place significant pressure on freshwater species relying on these ecosystems.

**Potential extinction risks posed to freshwater species with future dams**

The construction of existing dams may be associated with the extinction of a significant number of freshwater species (Fig. 8a). We found that, of the 86 extinct freshwater fish species, approximately 48% have dam construction listed as a threat factor in the IUCN threat analysis. Similarly, for the extinct mollusks and amphibians, 35% and 17%, respectively, have dam construction identified as a threat factor in the IUCN analysis. (Tables S7 and S8). Further analysis revealed that in regions designated for future dam construction, 148 critically endangered freshwater species are at similar risk, as their habitats intersect with proposed dam locations (Fig. 8b). In particular, freshwater fish are especially vulnerable, with 73 critically endangered species across 9 orders, primarily located in Asia and Europe, facing imminent threats. Thus, the development of these future dams could signal a potential extinction crisis for 11% of the critically endangered freshwater fish species in riverine ecosystems. In addition, some freshwater mammals, such as the functionally extinct Baiji (*Lipotes vexillifer*), may face an increased risk of extinction in the wild due to the construction of future dams.

**Changing trends in future dam development**

Our results revealed a strong correlation between the trend in future dam construction and the economic development levels of global countries. In particular, over half of existing dams were constructed by high-income



**Fig. 8 | Extinct and critically endangered freshwater species associated with dam development. a** Richness of extinct species in areas affected by existing dams. **b** Overlap between critically endangered species richness and future dam locations.

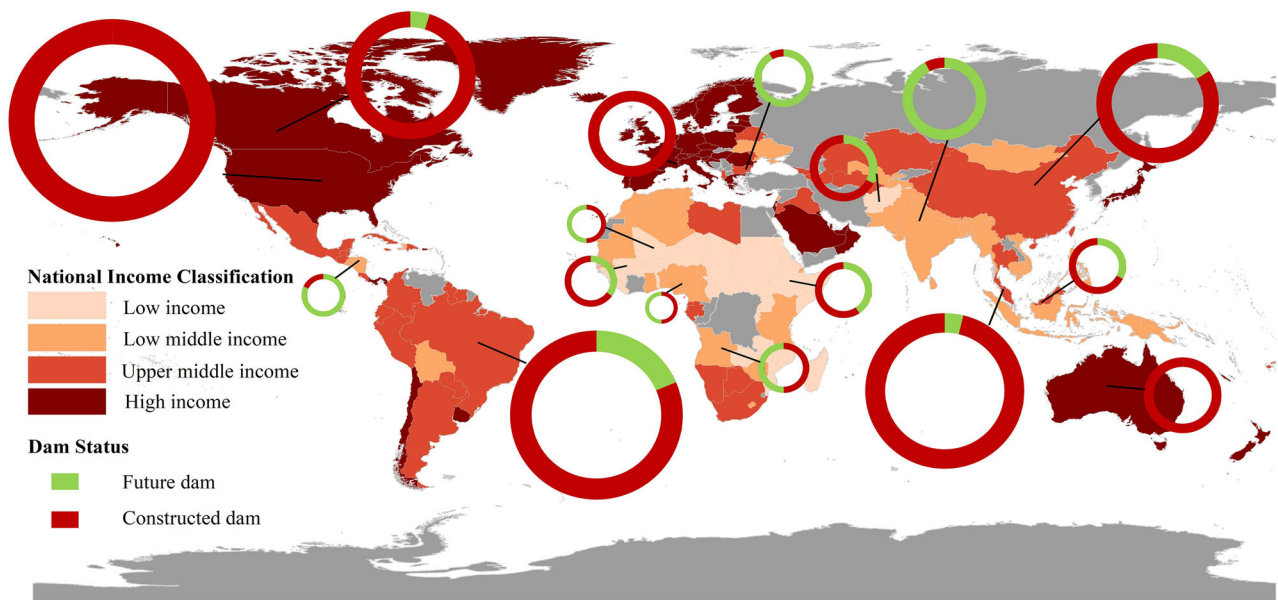
Representative species and taxa are illustrated with silhouettes and labels. (Animal icons are sourced from Phylopic.org and Wikipedia).

(36.2%) and upper-middle-income (38.4%) countries, with a fairly equal distribution between the two categories, while less than 1% of dams originated from low-income nations (Fig. 9). However, the majority of future dams were observed to be mostly planned in upper-middle-income (46.6%) and lower-middle-income (20.2%) countries, with a substantial reduction in the number from high-income countries (the decline from 36.2 to 8.7%) (Fig. 9). For instance, United States as a high-income country, had constructed 6975 dams in the past, yet planned only 10 dams for the future. High-income countries, such as Norway, Australia, and Germany, have

nearly no planned dams. Additionally, the proportion of planned dams in low-income and lower-middle-income countries, where biodiversity is not normally well protected, is much higher than that of high-income and upper-middle-income nations (Fig. 9).

### Discussion

The reduction in river connectivity attributed to dam construction is one of the main factors compromising fluvial ecological integrity<sup>43-45</sup>. This analysis shows that regions with a high concentration of threatened freshwater



**Fig. 9 | Spatial relationship between global dam development trends and national income levels. The background map indicates national income classification. Overlaid donut charts represent the proportion of existing (red) versus future**

planned (green) dams within each region. The size of the charts is illustrative of the relative total dam count.

species, such as the eastern Mississippi River basin, the Mekong River Basin, the Zambezi River, and the Yangtze River Basin, are characterized by dense dam distribution and low river connectivity<sup>46</sup>, which may contribute to increased extinction risk for these species. In this study, we employed the global river connectivity data with the highest spatial resolution available to evaluate the impacts of dams on different lengths of rivers<sup>42</sup>. We found that over 90% of river connectivity loss was driven by the degree of fragmentation. A cascade of adverse consequences would emerge from the decline in river connectivity. It obstructs the migration of freshwater species, preventing them from locating breeding grounds, foraging areas, and habitats, subsequently leading to a decrease in their populations<sup>47</sup>. One study has identified that if all planned dams are constructed in the future, over 260,000 km of rivers, including major arteries such as the Amazon, Congo, Irrawaddy, and Salween, will lose their free-flowing status, causing great potential damage to the ecosystems in these rivers<sup>48</sup>.

The construction of dams has profound impacts on biodiversity habitats through transforming rivers into reservoirs, subsequently submerging habitat areas in the vicinity of the dams. The construction of dams often involves damaging the wetland areas, such as marshes, estuaries, and lakes, which are essential ecosystems supporting a diversity of aquatic life, birds, and plants. The inundation caused by dams can lead to the complete loss of wetland habitats, affecting the survival of species unique to these wetlands, especially as benthic organisms, fish, and riparian vegetation face threats once riverbeds and banks are submerged. Since the 1970s, the construction of dams in developing countries in Africa, Asia, and South America has been on the fast rise, placing substantial environmental pressure on their key habitats, which has already caused damage to important natural habitats. It is projected that 63% of future dam constructions will be located within critical and natural habitats, a proportion markedly higher than the current presence of dams in such habitats. This trend is likely to result in more severe ecological damage.

Moreover, freshwater species face threats from the combined effects of multiple stressors, with dam construction and operation representing a major driver<sup>49</sup>. Additional pressures, including climate change, land-use change, overexploitation, pollution, and invasive species, interact to exacerbate habitat loss, population fragmentation, and declines in habitat quality<sup>18</sup>. Under certain conditions, dams may constitute the primary threat to specific endangered species, while other environmental and

anthropogenic factors can further amplify or modulate extinction risk. Therefore, reconciling the operation of dams with the health of freshwater systems remains one of the global challenges faced today, necessitating the implementation of effective measures to balance economic development with ecological conservation.

Our research indicated a potential link between dam construction and the extinction of some freshwater species. There have been around 30 freshwater species that became extinct or extinct in the wild within the global dam areas for the last 26 years, including 18 fish species, 10 mollusk species, 3 mammal species, and 9 amphibian species. In addition, the habitats of 201 freshwater species, listed as critically endangered (CR) on the IUCN Red List, overlap with dam areas (Table S8), and the ongoing construction of these proposed dams may exert pressure on these species<sup>50,51</sup>. The extent of dam impacts varied among taxa, with freshwater mammals comprising the highest proportion of species recorded as affected, followed by fish, amphibians, and mollusks. Although this study cannot determine that dam construction was the sole impact factor for causing the changes in the freshwater species within the study area, it can be identified as a direct or indirect leading factor threatening these species<sup>52,53</sup>. For instance, the Yangtze sturgeon (*Acipenser dabryanus*) was a species of freshwater fish native to the Yangtze River basin (Fig. S4). According to the IUCN assessment in 1996, this species was listed as critically endangered, and it was declared extinct in the wild in 2019. This shift was found to be primarily due to severe habitat destruction by the Gezhouba Dam and the Three Gorges Dam in the Yangtze River basin. Among freshwater mammals, the Ganges River dolphin (*Platanista gangetica*) is one of the most endangered cetaceans (Fig. S4). Its population has declined by more than 50% since 1957<sup>54</sup>. In India, at least 50 dams and barrages have been built, severely affecting the habitat, abundance, and population structure of the Ganges River dolphin. The biodiversity impacts of large-scale water development projects are often profound, affecting the physical environment, water quality, and biological communities.

Among freshwater species within the areas surrounding dams, freshwater mammals represent the largest proportion, followed by fish, amphibians, and mollusks. Few studies have examined the impacts of dams on freshwater taxa, such as mammals, amphibians, mollusks, and odonates. These existing assessments were largely confined to local or regional scales, missing the overarching cumulative effects of multiple dams within a single river system<sup>55–57</sup>. The construction of dams manifests a conspicuous barrier

effect, particularly for large freshwater mammals, including cetaceans, beavers, and otters. These species, with their extensive habitat range, are affected by habitat fragmentation resulting from dam implementation<sup>58</sup>. For instance, while specific populations, such as the European otter, may benefit from enhanced prey availability where fish congregate below dams<sup>59</sup>, the broader impact of dam construction is the severe disruption of longitudinal and lateral hydrological connectivity between upstream, downstream, and tributary systems, thereby impeding the migration routes and foraging corridors critical to the survival of otters<sup>14</sup>. Concurrently, alterations to riverbank morphology and habitat structure associated with dam development can inundate or remove nesting sites frequently utilized by otters, directly constraining their foraging efficiency and reproductive success<sup>60</sup>. These impacts are likely to result in range contractions and population declines. Moreover, the construction of dams has a severe impact on the habitats of mollusks. Dams lead to the submersion or fragmentation of habitats and alter water flow patterns<sup>61,62</sup>, which are detrimental to the survival and reproduction of mollusks.

The impacts of dams on freshwater species may vary significantly with size. Large dams, with their vast reservoirs and extensive inundation areas, profoundly alter ecosystems by disrupting hydrological cycles, breaking river connectivity, and reshaping habitats. Small dams, while individually affecting smaller areas with limited reservoir capacities<sup>63</sup>, pose substantial threats to small aquatic organisms and endemic species due to their high-density distribution and localized ecological impacts. These effects are particularly critical for habitat-dependent and endemic species. For example, insects and mollusks that rely on riparian wetland vegetation are severely affected by small dams<sup>64,65</sup>. However, distinct responses exist within mollusks: while the shift from lotic to lentic environments may benefit certain gastropods (e.g., snails) that prefer stagnant waters, it is often detrimental to freshwater bivalves (e.g., mussels). Bivalves rely on water flow for filtration and, critically, their life cycles depend on host fish for larval dispersal—a connectivity often severed by dam barriers<sup>66,67</sup>. To further enhance our understanding, future studies should employ more refined assessment methods to evaluate the varying impacts of dams of different types and locations on freshwater biodiversity across diverse environmental contexts.

The incomplete coverage of freshwater mollusks in the IUCN database may introduce potential biases into our analysis. Species with limited data might be either overrepresented or underrepresented, thereby affecting the accuracy of the research findings. Furthermore, species often face multiple, interconnected threats. In some cases, incorporating non-primary threat factors into risk assessments may lead to overestimation of risks, while certain critical threats may remain underexamined, further increasing the uncertainty of the results. These data gaps underscore the critical importance of enhancing global monitoring efforts and improving data collection for freshwater species. Such efforts are essential for more accurately predicting species' future trends and refining conservation planning.

Our study builds on previous research, showing that while dams serve as a source of renewable energy, they also potentially cause substantial damage to freshwater ecosystems. Additionally, existing studies indicate that reservoir areas, especially in tropical regions, may release substantial amounts of greenhouse gases, which contribute to global warming in a way that cannot be overlooked<sup>68,69</sup>. In response, nations worldwide have implemented strategies to better harness clean energy by establishing conservation areas near rivers or habitats affected by dams to safeguard freshwater species<sup>70</sup>, while national efforts to reconcile dam construction with the health of freshwater ecosystems should be supported by a range of policies, as emphasized by goals 6 (clean water and sanitation) and 15 (life on land) of the United Nations Sustainable Development Goals<sup>8</sup>.

## Conclusion

Although dams can significantly alter local ecosystems and have a lasting impact on freshwater biodiversity, quantitatively assessing the impacts posed by dams to freshwater species at a global scale remains to be undertaken. Using remote sensing big data techniques, along with the latest georeferenced global dam data and species distribution data, we conducted a

global analysis for assessing current effects of existing dams on all major freshwater species and predicting the potential future threats from the proposed dams on these species. Our results revealed that the proportion of freshwater species threatened near dams is much higher than in non-dam areas globally. Up to 85.19% of the species whose threatened category changed between 1996 and 2022 shifted towards worse types, which might be mainly attributed to the dam-induced river connectivity loss and habitat damage. In addition, we found that a high percentage of future dams are planned to be built in critical biodiversity habitats, especially in biodiversity hot spots of the global south countries. These proposed dam projects may place up to 11% of critically endangered (CR) freshwater fish in river ecosystems with extinction. This study has the potential to enhance our understanding of the impacts of dams on freshwater species and to offer valuable scientific guidance for the early-stage planning of future dam projects. Consequently, future decisions on energy infrastructure should go beyond economic metrics and explicitly account for biodiversity costs, ensuring that renewable energy targets are not met at the expense of freshwater species extinction.

## Methods

### Data of current and future dams

The global dam tracker (GDAT) database was used in this study to represent the location and construction attribute of existing global dams<sup>10</sup>. Released in 2023, GDAT encompasses the information of totally 35,140 dams. Based on the existing dam databases, GDAT was established by integrating national and regional dam databases across the world with information available from different institutions, such as governmental agencies, academic institutions, and non-profit organizations<sup>10</sup>. This dataset has been systematically validated with Google Earth and other geospatial products. GDAT is currently one of the most comprehensive georeferenced global dam databases. Compared to the other commonly used dam data, such as the Global Georeferenced Database of Dams (GOODD)<sup>71</sup> and GeoDAR<sup>72</sup>, GDAT not only contains more dams but also was updated with more detailed attributes, including the construction date and use purpose of the dams.

The future dam data was published in 2015, which comprises 3700 hydropower dams with total capacity exceeding 1 gigawatt<sup>50</sup>. Among these recorded dams, 83% are in the planning stages, while 17% are under construction<sup>50,73,74</sup>. These data were created from information from over 350 scientific references, governmental and non-governmental sources, as well as other public databases, reports, and newspaper articles. Moreover, we removed the dams that have been built and are duplicates in the GDAT database, leaving 2989 proposed dams. Utilizing this future dam data, we identified regions slated for upcoming dam construction and projected the potential impacts of such developments on freshwater biodiversity.

### The red list assessment of global threatened species

We utilized the geographic range data of freshwater species from the IUCN Red List of threatened species to assess the threat status of species in the vicinity of dams and the temporal changes in their threat categories following dam construction.

The IUCN Red List encompasses global assessments of over 23,000 freshwater species and serves as a benchmark for gauging the current status and trends of aquatic biodiversity<sup>75</sup>. It systematically ranks species' risk of extinction, ranging from extinct (EX) and extinct in the wild (EW) through the threatened designations of critically endangered (CR), endangered (EN), and vulnerable (VU), and extending to near threatened (NT) and least concern (LC). When a taxonomic unit lacks sufficient information, preventing a direct or indirect assessment of its extinction risk based on its distribution and/or population status, it is designated as data deficient (DD) (Table S9). Species classified as DD were excluded from our study. To quantitatively assess the temporal dynamics of extinction risk, we extracted the historical Red List categories for each species spanning from 1996 to 2022 directly from the IUCN database. We utilized these retrospective records to identify specific shifts in threat status over the study period. Furthermore, we cross-referenced the selected species with time-stamped

occurrence records (specifically, observation coordinates and collection dates) from the Global Biodiversity Information Facility<sup>19,76</sup>. As IUCN range maps are static expert-derived representations of potential distributions rather than confirmed records of real-time presence<sup>77</sup>, this step was employed strictly to verify species presence, ensuring their documented occurrence within dam-affected regions during the analysis period. Regarding spatial data structure, the geographical ranges of freshwater species were obtained from the IUCN Red List in the form of vector polygons, which were then mapped onto sub-basins and lakes using the HydroBASINS layer. We first selected species explicitly identified in the IUCN Red List as threatened by dams and water management/use (threat category 7.2) and assessed the impacts of dams by analyzing their temporal dynamics. However, since IUCN threat categories are based on expert judgment and existing data, which are infrequently updated and do not provide complete taxonomic coverage, this limitation may result in certain species indirectly affected by dams being unrecorded. “To ensure the comprehensiveness of our analysis, we expanded our selection to include additional taxa identified primarily through spatial overlay analysis (specifically, where species distributions intersect with dam influence zones; Table S10), supplemented by literature reviews and expert knowledge (Table S11). Consequently, the final selection derived from the IUCN Red List encompasses five major freshwater taxonomic groups: fish, mammals, mollusks, odonates, and amphibians (Table S11).

### Map of the world’s free flowing rivers

We integrated the global dam tracker (GDAT) database with the “FFR” dataset to recalculate the connectivity status index (CSI) of global rivers<sup>42</sup>. Based on the recalculated CSI, we assessed the spatial relationships between dam locations, river fragmentation, and the distribution of freshwater species<sup>19</sup>. Specifically, we utilized the spatial data from the FFR assessment to characterize the connectivity status of 12 million km of global rivers, identifying those segments that maintain free-flow throughout their entire length<sup>78</sup>. The CSI quantifies river connectivity on a scale from 0 to 100% for each individual segment from source to outlet across a basin or network; in this study, rivers with a CSI of 95% or higher were designated as free-flowing rivers.

### Natural and critical terrestrial habitats

Data on natural and critical habitats were used to evaluate the impacts of constructed dams and assess whether planned dams align with biodiversity conservation standards, such as the International Finance Corporation (IFC)’s Performance Standard 6 (PS6)<sup>79</sup>. While this analysis is not exclusively targeted at freshwater species, it provides valuable ecological context by identifying risks to terrestrial habitats that are closely linked to freshwater ecosystems. Many freshwater-dependent species, such as mammals (e.g., otters), amphibians (e.g., frogs and salamander), and dragonflies, rely on the interplay between terrestrial and freshwater habitats for their survival.

In 2018, Brauner et al. released “critical habitat in the terrestrial realm” based on IFC PS6 guidelines<sup>80</sup>. The term “critical habitat” refers to areas of high biodiversity value, which are crucial for threatened, endemic, congregating, and migratory species, as well as endangered or unique ecosystems, and pivotal evolutionary processes<sup>79</sup>. Such habitats offer support during the early stages of a project’s life cycle to facilitate risk-mitigation planning. This dataset is broadly categorized into: protected areas; key biodiversity zones; threatened ecosystems; critical locations for selected species (such as tigers and sea turtles); and distribution ranges of threatened species that meet the IUCN Red List Criterion D.

The “natural and modified habitat” dataset was released in 2020<sup>81</sup>. It aligns closely with the IFC PS6 definition of natural and modified habitats: regions comprised primarily of viable combinations of plant and/or animal species that are indigenous, and/or areas where human activities have not fundamentally altered the primary ecological functions and species composition. This dataset offers high spatial resolution (≤1 km) on biological habitats, making it suitable for preliminary assessments by businesses involved in selecting natural and critical habitat projects. Based on the

mentioned key habitat data, this study quantified the area of critical habitats within the influence range of dams. This is a crucial issue for investors to consider in the early stages of dam development, aiding in the improvement of decision-making processes.

### Species richness within dam influential areas

We utilized the IUCN Red List and relevant literature, along with dam location data, to assess the conservation status of freshwater species within the regions affected by dams<sup>10</sup>. These regions were defined as areas where the geographical ranges of freshwater species overlap with dam locations. In total, there were 14,260 species identified globally, encompassing amphibians, freshwater fish, freshwater mammals, freshwater mollusks, and Odonata (Table S1). The species list encompasses not only those explicitly tagged with threat code 7.2 (threatened by dams and water management/use) in the IUCN database but also additional taxa identified through the spatial overlay analysis and literature review. Crucially, as all identified species are listed in the IUCN Red List, we retrieved their official conservation status (e.g., CR, EN, and VU) directly from the IUCN database to compute the threat proportions in the subsequent equations (Eqs. 1–3).

We then created maps presenting the proportion of endangerment among these five species categories. For each of the species’ category, distribution maps of threatened species (falling under the CR, EN, and VU categories) were overlaid onto a hexagonal grid with a side length of 50 km<sup>69,82</sup>. Hexagonal grids, widely used in biodiversity studies, reduce directional bias due to their uniform and compact nearest-neighbor relationships<sup>83</sup>, making them effective for modeling movement pathways, connectivity, and ecological processes<sup>84</sup>. This grid is based on an icosahedron, which is then projected onto a sphere using the inverse Icosahedral Snyder equal area projection, taking into account the Earth’s sphericity. The number of species within each hexagonal grid was then summed to derive the richness of threatened species in that unit. When calculating the proportion of species under threat, we first calculated statistics for each of the five species categories, followed by a comprehensive summary.

The formula was applied as below (assuming the ratio between data-deficient species and non-data-deficient species remains consistent across the categories):

$$Prop_{threat} = \frac{CR + EN + VU}{N - DD} \tag{1}$$

where  $N$  represents the total sample size, CR, EN, and VU denote the counts of species categorized as critically endangered, endangered, and vulnerable, respectively.

This method of evaluating threat levels has been widely adopted in numerous previous studies, which is a current consensus among conservation biologists on how to study the proportion of threatened species<sup>85,86</sup>. Due to the uncertainties associated with DD species, this approach to calculating threat proportion is inherently conservative. Often, DD species are either rare or exhibit limited distribution ranges, making them challenging to assess. While some DD species might eventually be categorized as threatened, others could be classified as LC. Thus, to capture and illustrate this inherent uncertainty, upper and lower bounds for the threatened species proportion have been established as below:

$$Prop_{threat} = \frac{CR + EN + VU}{N} \tag{2}$$

$$Prop_{threat} = \frac{CR + EN + VU + DD}{N} \tag{3}$$

Equation (2) denotes a scenario where none of the DD species are threatened, representing the lower margin for the proportion of species at risk. Conversely, (3) signifies a situation in which all DD species are under threat, constituting the upper margin for the proportion of endangered species.

### Extinction risk of species under hydro dam's impacts

The cumulative effects of dams on freshwater ecosystems can be manifested over time. To quantitatively assess the impact of dam construction on species in a temporal scale, we investigated the changes in extinction risk for all species after the construction of dams<sup>87</sup>. Firstly, species designated as “DD” were excluded from our analysis due to their persistent lack of sufficient data, making it difficult to identify their environmental threats. We then identified the changes in each species' threat categories between 1996 and 2022, using the retrospective review of species category changes by the IUCN. In particular, all species with shifts in threat categories were classified into two groups: high-risk transitions and low-risk transitions<sup>88</sup>. The high-risk group encompasses species that were initially classified as threatened or Near Threatened and maintained this classification throughout the study duration, as well as species that migrated from a lower to a higher category of threat. Conversely, the low-risk group indicates species that remained within the “LC” designation during the study time, or those that transitioned from a higher to a lower category of threat (Fig. S5).

We applied a geospatial congruence analysis to quantify the spatial overlap between dams and the distributions of threatened freshwater species. First, we extracted records of extinct freshwater species that were explicitly linked to dam- and water-management-related threats in the IUCN classification, and projected their historical distributions to identify regions of elevated extinction risk. We then examined critically endangered freshwater species currently threatened by dams, grouping them by taxonomy and ecological traits, and mapped their distributions relative to planned dam locations. This framework enabled us to highlight spatial hotspots where planned dam development may coincide with highly threatened species, thereby informing both conservation prioritization and infrastructure planning.

### Freshwater species threats in dam-induced non-free-flowing rivers

This study evaluated the impacts of dam-induced NFFRs on freshwater species. NFFRs exceeding 10 km in length were identified, and the conservation status of freshwater species relying on these rivers as part of their habitat was assessed. To further quantify these impacts, population trends were also analyzed using IUCN data. Additionally, a species richness map of dam-fragmented rivers was developed by mapping the distributions of threatened freshwater species onto NFFRs, ultimately identifying biodiversity impact hotspots.

Ecoregions are defined as spatial units characterized by relatively homogeneous ecological features, climate conditions, vegetation types, and ecological processes. After identifying river connectivity loss caused by dams and the associated distribution patterns of freshwater species, we further tested whether this spatial overlap reflects quantifiable statistical relationships. To this end, we conducted correlation analyses at the ecoregion scale, using the proportion of NFFRs (proportion of NFFR) as an indicator of anthropogenic hydrological modification, and the average number of threatened species (avg. TS) and the average population decline of species (avg. DS) as biodiversity response variables. For each ecoregion, Pearson's correlation coefficients ( $r$ ) and their significance levels ( $p$ -values) were calculated to assess the statistical associations between the degree of river fragmentation and the level of species threat or population decline.

### Impacts of existing and future dams on biodiversity habitats

We follow the IFC PS6 to assess the risks of dams to natural and critical habitats. Building on this initiative, our study utilized the latest datasets of critical and natural habitats and conducted overlay analysis to identify how existing dams intrude upon these vital habitats. The environmental impacts of dams vary with size and can extend to the outer boundaries of watersheds. To account for this variability, dams were classified by reservoir capacity: small dams (<1 million cubic meters), medium dams (1–10 million cubic meters), and large dams (>10 million cubic meters). A buffer-based approach (Table S10) was then used to define the “region of dam influence,” approximating both the watershed and reservoir

surface area as concentric circles around each dam (Fig. S6). The diameters of these circles represented the maximum and minimum distances from the dam's center. For dams without reservoirs, the buffer zone was set to 1 km (see equations in Supplementary Note 1). This approach provided sufficient variation in buffer sizes to assess the impacts of different dam sizes on habitats, rivers, and species. Similarly, future dams must also adhere to PS6 standards. To evaluate their potential impacts on terrestrial habitats, buffer zones of varying distances were applied to proposed dam sites using the same methodology. This approach captured the fragmentation effects of reservoir inundation on adjacent habitats. For dams lacking reservoir area data, buffer zones were estimated based on dam size, referencing existing dams. An arithmetic means between maximum and minimum impact distances was used to analyze the variability in dam impacts across distances.

### Data availability

The datasets used in this study are publicly available. Dam data were obtained from the global dam tracker (GDAT; accessed 30 December 2024). Species conservation status and range data were obtained from the IUCN Red List (accessed 30 December 2024; subject to IUCN terms of use). River connectivity data were obtained from the global free-flowing rivers dataset (Grill et al. 2019; accessed 30 December 2024). The Source data underlying the figures and tables, and other derived and aggregated datasets supporting the findings of this study, are publicly available via Zenodo (<https://doi.org/10.5281/zenodo.18348239>). Original third-party spatial datasets (e.g., IUCN species range polygons) are not redistributed due to licensing restrictions; the Zenodo repository provides derived outputs sufficient to reproduce the analyses and visualizations reported in this study.

### Code availability

Custom code used for data processing and analysis is available from the corresponding authors upon reasonable request.

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## Competing interests

The authors declare no competing interests.

## Additional information

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