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Safeguarding migratory fish via strategic planning of future small hydropower in Brazil

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Small hydropower plants (SHPs) are proliferating globally, but their cumulative threat to blocking migratory fish and the fisheries that these fish sustain has been underappreciated when compared with large hydropower plants (LHPs). Here, we quantified the trade-offs between hydroelectric generation capacity and the impacts on river connectivity for thousands of current and projected future dams across Brazil. SHPs are the main source of river fragmentation, resulting in average connectivity losses of fourfold greater than LHPs. Fragmentation by SHPs is projected to increase by 21% in the future, and two-thirds of the 191 migratory species assessed occupy basins that will experience greater connectivity losses due to SHPs than LHPs. A Pareto frontier analysis identified future dam portfolios that could halve the number of hydropower plants that are required to deliver the same energy-generation capacity compared with the least-favourable solutions, while simultaneously resulting in lower river fragmentation and protecting numerous undammed basins. Our results highlight the need for strategic planning that considers the unprecedented growth and cumulative effects of SHPs.

Rapid expansion of hydropower dams threatens many of the remaining free-flowing rivers in the biodiverse tropical regions of the world, interrupting the migrations of freshwater fishes on which millions of people rely directly for their livelihoods[1–3]. As a consequence, there is a growing need to carefully balance the trade-offs between hydropower production and ecosystem functioning to avoid biodiversity losses and ensure long-term food security and income[3,4]. Considerable scientific activity and international scrutiny remain focused on LHPs, whereas the environmental repercussions of smaller projects have been largely overlooked in broad-scale energy policies and garner little public attention. Despite (and perhaps due to) this oversight, a series of political and economic incentives for renewable energies have been implemented across the world to benefit projects that are labelled as SHPs—which are often defined as plants with a generation capacity of less than 10 MW—but this threshold may vary among countries[5]. These incentives assume that, in addition to the lower energy generation capacity of SHPs, 'small' also equates to low environmental impacts. This has ultimately led to licensing exemptions, favoured energy prices (for example, feed-in tariffs) and subsidized loans that fuel increased construction[5–8]. However, emerging scientific evidence suggests that the ecological impacts of SHPs can be disproportionally high for their societal benefits[9,10].

The primary concern with rapid SHP development is that their number dwarfs that of LHPs. Today, more than 80,000 SHPs are operating in at least 150 countries (11 times the number of LHPs) and the construction of tens of thousands of new dams is projected[5]. Despite being widespread, the aggregate contributions of SHPs to electrical grids are often quite low. For example, according to Brazilian regulations, SHPs are defined as those with a generation capacity below 30 MW. Although they represent more than 85% of the 1,517 hydropower plants operating in the country, they are responsible for only 7% of total generation capacity[11]. The imbalance between the number of power plants and their generation capacity calls into question whether the marginal contributions by SHPs to national-level energy requirements are worth their potential environmental and societal costs. The cumulative impacts of SHPs on basin-wide hydrology and habitat connectivity may exceed that of LHPs when standardized by hydropower generation[9,10], therefore challenging the majority of environmental policies that focus on the impacts of individual, and often large, dams[5,12].

Owing to their sheer number and geographical extent, the widespread proliferation of SHPs may be an important, yet underappreciated, threat to the persistence of migratory fishes and the fisheries and diverse societal values that they support[3,13]. Dams constrain the movement of migratory fish along river networks and isolate critical habitats that are necessary for their life history (for example, spawning and feeding grounds), resulting in local extinctions, population declines and collapses of fishery stocks[14–16]. As a consequence, migratory fish species are among the most vulnerable organisms to hydropower development in the tropics[17], which is concerning considering their high ecological and socioeconomic importance. For example, migratory species have key roles in food webs and ecosystem functioning[18,19], and are included among the top-ranked inland fisheries on the basis of market values and cultural preferences[15,20]. Past and planned dam construction greatly exacerbates the loss and fragmentation of habitat in dendritic river networks through the cumulative effects of multiple barriers[21,22] and therefore threatens the persistence of migratory fish and the resilience of fisheries[23].

Optimal siting of new dam construction is paramount when attempting to balance the trade-offs between hydropower generation and the river fragmentation that threatens migratory fish[24], yet it is noticeably absent from many national energy plans. Managers and decision makers have a wide range of options to help to guide the location on the landscape at which prospective hydropower projects may be constructed[25]. Recent attention has focused on the use of trade-off assessments of multiple objectives to identify win–win management opportunities and provide more prescriptive recommendations, which are both highly desirable in decision-making[26]. Trade-off analyses can evaluate the performance of prospective

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hydropower plant portfolios by comparing their cumulative ecological impacts and generation capacity gains to meet desired future energy demands[27–29]. Thus, these analyses offer an alternative that looks beyond the 'more is better' perspective[5,25] to identify portfolios of SHPs and LHPs that maximize energy generation while minimizing the loss of river connectivity.

The duality of growing hydropower demand for future energy supply and the major socioecological value of migratory fish in developing countries necessitates a robust examination of the trade-offs between future SHP and LHP development and the resulting fragmentation of rivers. In this Article, we explore this issue in Brazil—a global leader in hydropower development[5]—where more than 2,200 new hydropower projects are presently in different stages of the licensing and inventory processes. First, we compared the cumulative effects of current and projected future SHPs and LHPs on the network connectivity of Brazilian rivers; here, we defined cumulative effects as the fragmentation by dams in aggregate. Second, we quantified the resulting range-wide loss of connectivity for 191 migratory fish species, including both those that are on the national IUCN Red List and those that are highly valuable for commercial or recreational fisheries. Third, we explored the trade-offs between gains in energy generation capacity and loss in river connectivity to inform strategic planning for the development of new hydropower construction in the country.

Here we adopted the dendritic connectivity index (DCI) as our metric of connectivity[22], which is an estimate of the probability of a fish being able to disperse between two random points in a given river network. Empirical research has shown that DCI can accurately describe the effects of river fragmentation and dispersal limitation on the spatial distribution of fish species[30,31], and it has been used in different parts of the world to assess the impacts of fragmentation by dams[13,32,33]. We computed the DCI for all Brazilian basins according to the present-day (2018) and projected future (around 2050) distribution of dams, contrasting the respective contributions of SHPs and LHPs over time and space. Our results compose a national-level assessment of current and future fragmentation by hydropower that informs future energy and environmental policies through a trade-off analysis exploring a large number of possible future scenarios.

Contributions of SHPs and LHPs to river fragmentation

The construction of hydropower dams has resulted in the widespread fragmentation of Brazilian river basins over the past century, with an average basin-level loss in river connectivity (DCI) from 100 to 83, representing a decrease of 17 units (a DCI of 100 indicates a completely free-flowing basin with no artificial barriers; Fig. 1). SHPs alone contributed to an average decrease of 14 ± 21 s.d. DCI units, four times more than the average decrease observed for the LHP-only scenario (4 ± 11 s.d. DCI units). The decrease in river connectivity associated with historical SHP construction mirrors the overall trends, indicating that SHPs made a disproportional contribution to river fragmentation over the last century. Fragmentation rates remained relatively steady through time until a marked acceleration in recent decades (Fig. 1). Whereas fragmentation rates due to LHPs remained constant, the loss of connectivity caused by SHPs increased by sevenfold after the year 2000, fuelled by numerous governmental incentives[5].

The 2,268 new hydropower projects that are presently in different stages of construction and potential approval that were evaluated in this study will compromise future river connectivity throughout Brazil, primarily driven by new SHP construction. Overall, future dam construction is expected to cause a 24% average loss in river connectivity (from a present-day average DCI of 83 to 62 projected by around 2050), with decreases in individual basins ranging from 0% to 89% (Fig. 2a). This predicted loss is caused principally by anticipated SHP construction (average DCI decrease of 20%) compared with LHPs (4%). River fragmentation by hydropower has been historically more concentrated in basins located in the southeastern and southern portions of the country—in the Paraná, Uruguay and East Atlantic Basins (Fig. 3). Fragmentation by SHPs will continue to increase in these basins, as well as expand in the central-west and north regions over time.

The growing footprint of river fragmentation is predominantly the result of projected increases in new SHPs that are more widespread over the country and with numbers that far exceed those of LHPs (Fig. 3). As a consequence, 424 basins that are presently free of hydropower will have new SHPs in the future, representing the primary driver for future nationwide loss in river connectivity. A closer examination of basins that are presently free of hydropower reveals that river connectivity will decrease by more than one-third (35% ± 22% s.d.) in response to future dam construction—an outcome that is again driven by SHPs (Fig. 2b). A decrease in the connectivity of basins that are already impacted by hydropower is also predicted (Fig. 2c).

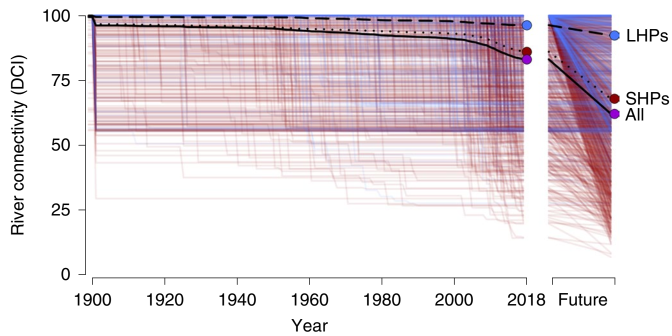

Fig. 1 | Temporal trends in river connectivity in Brazil according to changes in DCI over the past century and future projections due to ongoing and planned dam construction. The coloured lines represent yearly estimates of DCI for 1,216 individual basins; the lines indicate the unique contribution of SHPs (red) and LHPs (blue). The black lines represent average values for SHPs (dotted), LHPs (dashed) and all types of hydropower combined (solid). 'Future' reflects ongoing and planned construction that is projected to occur mid-century (around 2050); the exact year is subject to change depending on local-level factors, future policies and governance.

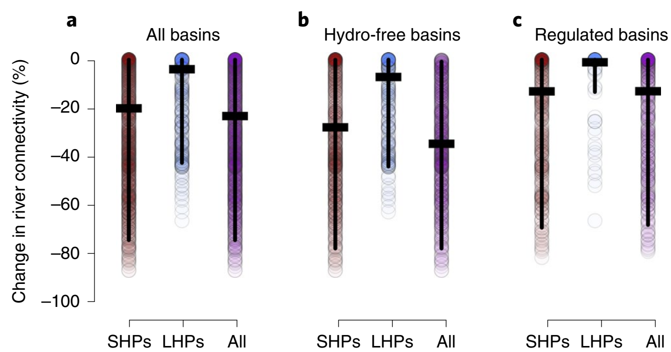

Fig. 2 | Predicted future change in river connectivity. a–c, The predicted future percentage change in river connectivity (DCI) from the present-day (2018) to mid-century (around 2050) for the Brazilian basins according to the separate contributions of SHPs (red), LHPs (blue) or all types of hydropower combined (purple). The black bars indicate the average values and the black lines indicate the 95% confidence intervals. Results are shown for all 1,216 basins (**a**), 573 basins that are currently free of hydropower (**b**) and 643 basins that are presently regulated by hydropower (**c**).

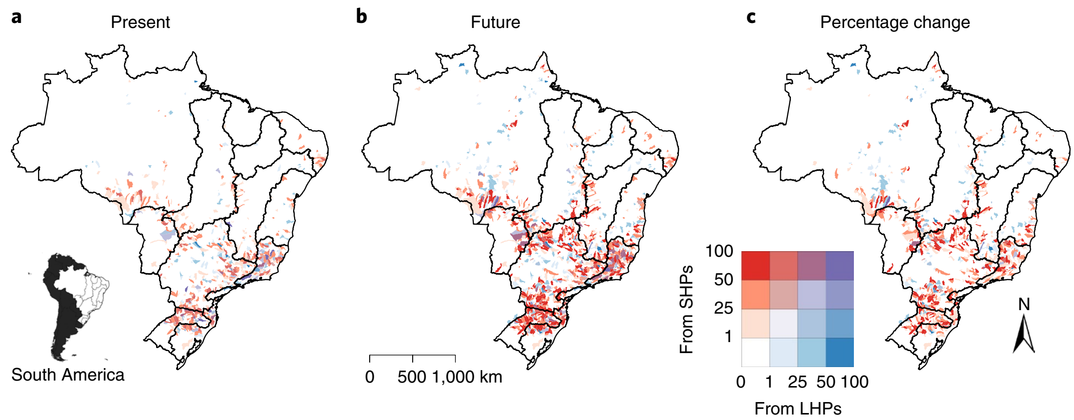

Fig. 3 | Present and projected future river connectivity. a–c, Present (2018) (**a**), future (circa 2050) (**b**) and projected percentage change (**c**) in river connectivity (DCI) for the Brazilian basins according to the contributions of SHPs (red shades) and LHPs (blue shades). The colour palettes represent values of absolute DCI loss from free-flowing state (that is, 100 – DCI) (**a** and **b**) or percentage loss between periods (negative change in all cases) (**c**). The black lines delimit the boundaries of the major Brazilian hydrographic units.

Consequences of river connectivity loss for migratory fishes

Further river fragmentation caused by planned SHPs is also expected across the geographical range of migratory fishes, including species that are at risk of extinction and those that support highly valuable commercial or recreational fisheries. The respective contributions of future SHPs and LHPs to river fragmentation in the ranges of migratory species are relatively similar at present (Fig. 4a), but the relative fragmenting effects of SHPs are expected to rise. Close to two-thirds (62%) of all migratory species occupy basins that will experience greater fragmentation due to SHP construction compared with LHP construction in the future (Fig. 4b).

The detrimental effects of fragmentation by planned SHPs are manifested in at least part of the geographical range of 14 red-listed species and 20 species of highest value for fisheries (out of 24 species for each category; Methods), resulting in an expected DCI decrease of more than 10% in basins occupied by the majority of these species. For example, a 28% decrease in river connectivity by SHPs is expected in the subset of the geographical range of *Brycon vermelha* in which hydropower has been developed. This red-listed species is endemic to the upper portions of the rivers Mucuri and São Mateus, and SHPs were identified in conservation status assessments as one of the main threats to the persistence of the species[34]. Furthermore, average decreases in river connectivity by SHPs of more than 10% are expected in basins occupied by 12 species of high value, including *Prochilodus lineatus*, *Megaleporinus obtusidens*, *Pseudoplatystoma corruscans* and *Salminus brasiliensis*, which are top ranked in market prices, recreational importance and yields in the Paraná, Paraguay and Uruguay Basins[15,35]. Results for all 191 species are provided in Supplementary Table 1. We also repeated the entire analysis with a modified measure of connectivity that accounts for situations in which migratory fish populations are predominantly composed of external immigrants from downstream basins (Supplementary Methods). All of the results were similar to those presented above, except for greater losses of river connectivity due to both planned LHP and SHP construction (Supplementary Figs. 1–6).

Trade-offs between energy gains and river fragmentation

Energy regulations stipulate that generation capacity is an indicator of the potential environmental impacts of a hydropower plant. However, there is little association between the generation capacity of individual future hydropower projects and their predicted effect on river connectivity (Fig. 5). This is the case for all hydropower plants combined (Pearson $R = 0.23$), only SHPs ($R = 0.18$) and only LHPs ($R = -0.01$). The projected effect of each future hydropower project on river connectivity is shown in Supplementary Table 2.

We simulated 4.3 million scenarios to evaluate portfolios of different numbers and identities of planned hydropower projects that optimize nationwide gains in generation capacity while balancing reductions in river connectivity. Although river connectivity and gains in generation capacity are inversely proportional, there is considerable variability in this relationship among dam portfolios (Fig. 6a). The Pareto frontier operator identified 207 favourable and 221 least-favourable dam portfolios (the remaining were considered to be intermediate solutions), of which 33 and 45, respectively, fall inside the range of projected hydropower demands for Brazil in the 2030–2040 period.

A closer examination of the projected generation capacity revealed that the least-favourable portfolios generally involve excess construction of hundreds of SHPs to achieve the same total energy generation capacity (Fig. 6b and Supplementary Table 3). Favourable portfolios have on average 430 SHPs (±174 s.d.) and 58 LHPs (±21 s.d.), whereas least-favourable portfolios have more than twice these numbers, averaging 1,138 SHPs (±243 s.d.) and 118 LHPs (±30 s.d.). Furthermore, the number of basins that remain free of hydropower in favourable portfolios is twofold higher than in least-favourable portfolios (Fig. 6c); on average, 202 (±67 s.d.) and 394 (±57 s.d.) basins will no longer be free of hydropower in favourable and least-favourable portfolios, respectively. For example, a new input of 25 GW can be achieved with 64% fewer SHPs (784), 57% fewer LHPs (77) and by damming 50% fewer free river basins (204), ultimately resulting in a twofold lower decrease in river connectivity ($DCI_{present\text{-}day} = 83$, $DCI_{favourable} = 77$, $DCI_{least\text{-}favourable} = 68$) compared with the least-favourable portfolio. These results highlight that there is remarkable scope for optimal siting of planned new dams in the coming decades, therefore supporting the importance of strategic planning and trade-off analysis to avoid excessive SHP construction that leads to needless loss in river connectivity.

Implications and recommendations

The nationwide proliferation of SHPs in Brazil has caused substantial disruption of river connectivity in recent decades, threatening the persistence of migratory fish species on which ecosystems and humans depend. Losses in connectivity are predominantly driven by SHPs, exceeding the impacts of LHPs in most basins across Brazil. This finding supports the growing notion that SHPs in high densities can collectively outweigh the effects of LHPs on river connectivity despite the usual spatial centrality of larger dams in

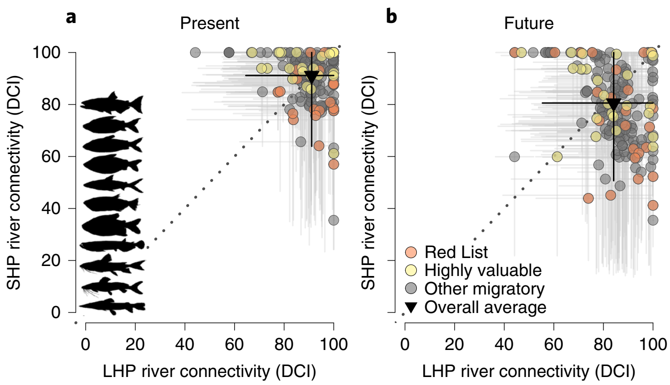

Fig. 4 | The effects of SHPs and LHPs on river connectivity. a,b, The effects of SHPs and LHPs on river connectivity (DCI) in basins occupied by 191 migratory fish species according to present-day (**a**) and projected future (mid-century) (**b**) dam distributions. Average river connectivity across each species' geographical range (that is, occupied basins out of the 1,216 basins) are represented by coloured circles. The grey lines show the 95% confidence interval. Red-listed species (24, orange), species that are highly valuable for fisheries (24, yellow) and the remaining species (grey) are indicated. The black triangles and black lines indicate the overall averages with the associated 95% confidence intervals. The main taxonomic groups that are classified as migratory are illustrated in **a** (from top to bottom, Bryconidae, Prochilodontidae, Anostomidae, Curimatidae, Hemiodontidae, Triportheidae, Serrasalmidae, *Rhaphiodon* (Cynodontidae), *Pterodoras* (Doradidae), *Rhamdia* (Heptapteridae) and Pimelodidae). The full species list is provided in Supplementary Table 1.

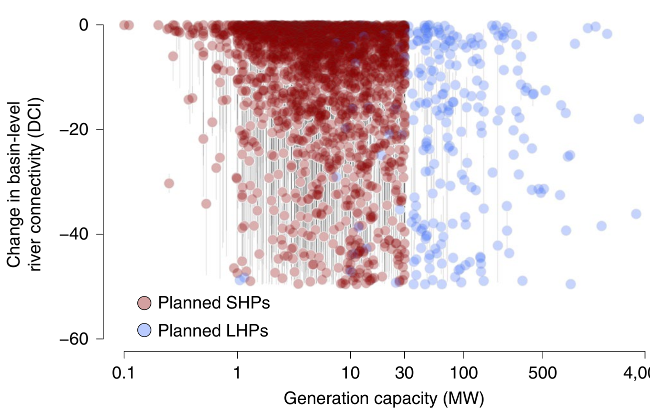

Fig. 5 | Relationship between the generation capacity of each future hydropower project and its effect on river connectivity (DCI) at the basin level. Estimates of average DCI loss (the average difference across all basin-level future scenarios with and without each dam) for planned SHPs (red) and LHPs (blue) are represented by circles, and the grey lines indicate the range. The 24 planned LHPs with a future capacity of less than 30 MW were classified as such by the energy agency ANEEL on the basis of other criteria, such as reservoir area (that is, >13 km^2).

river networks[5,9]. As conflict over water resources increases under growing population and energy demands, ecologically sustainable hydropower development in developing countries will necessitate that rivers be managed for multiple co-benefits[24].

River fragmentation is on the rise in Brazil and accelerated in the early 2000s, during which construction rates of SHPs increased 13-fold in comparison to the previous decade[5]. This boom in SHP construction followed a series of policy incentives that included new regulations for the energy market, a relaxation of size classification criteria, simplified environmental licensing and economic encouragements, such as feed-in tariffs and subsidized loans by public banks[5,36]. For example, the first feed-in tariff policy in the country was implemented in 2004 and resulted in 59 new SHPs in just eight years[37]. Our results reveal that, although basins located in the Paraná, Uruguay and East Atlantic river systems have been more heavily fragmented by SHPs, river fragmentation in the northwestern Brazilian Highlands has increased substantially in recent decades. This includes the upper mainstem portions and tributaries of important rivers such as the Tocantins, Araguaia, Madeira, Tapajós, Xingu, São Francisco, Paraguay and Paraná.

Increased fragmentation of Brazilian rivers is imminent; thousands of SHPs are presently undergoing planning, licensing and construction. These dams, in contrast to LHPs, are expected to be the predominant source of future habitat fragmentation for two-thirds of the migratory fish species in Brazil, including species of high conservation priority and socioeconomic importance. In the Tapajós River Basin, which is among the most vulnerable rivers of the Amazon Basin for hydropower development[38–40], growing conflicts and judicial battles have arisen over the proliferation of SHPs in some of its tributaries[12]. One of the most controversial cases is in the Juruena River in Mato Grosso, where the implementation of eight SHPs is affecting the fisheries of the Enawene Nawe people—an essential component of their culture, spiritual practices and food security[41]. Here we report that 14 basins of the Tapajós Basin may lose more than 50% of their river connectivity due to planned SHP construction (eight of them part of the Juruena Sub-basin), and the projected loss is as high as 85% for the Cupari Leste and Buriti basins.

Empirical evidence suggests that changes in the structural connectivity of rivers reduce biodiversity and affect the composition of fish communities through dispersal limitation[30], highlighting the high vulnerability of migratory species to fragmentation[14]. Our estimates indicate that there will be a 40% decrease in river connectivity caused by future SHPs in basins supporting the following red-listed species: *Steindachneridion doceanum*, *Rhamdia jequitinhonha* and *Brycon opalinus*. Moreover, the species *P. lineatus*—one of the most collected species in the Paraná, Paraguay and Uruguay Basins, where the yields of fisheries in some portions reach 30,000,000 kg annually[15,35,42]—occupy river basins that are expected to experience a 19% connectivity loss from SHPs alone. These examples call for heightened investigation of how rampant SHP development may compromise sustainable fisheries practices and threaten the persistence of migratory species in the future. The current understanding of fish migratory dynamics in Brazil is quite limited and did not allow us to refine our analysis to include the actual migratory routes of the species. We highlight this as a future research need to further inform the strategic planning of hydropower development.

Optimization approaches have provided renewed hope for reducing what have previously been considered inevitable environmental and social conflicts involving hydropower development[4,26]. Our study indicates that informed selection, or portfolios, of new dams can both meet future energy demands of Brazil and concurrently minimize the resulting loss of river connectivity. In fact, through a careful planning process, favourable dam portfolios more than halve the number of both SHPs and LHPs compared with least-favourable dam portfolios, while delivering the same total energy generation capacity. This amounts to hundreds fewer dams being constructed, substantially decreasing the degradation of river connectivity and effectively protecting numerous basins that are presently free of hydropower.

Results from this study support previous investigations in other parts of the world that demonstrate the strength of varied trade-off analyses in balancing hydropower production and dam-induced effects on floodplain fisheries, greenhouse gas emissions and sediment trapping[27–29]. However, important challenges persist. Our findings imply considerable cost reductions as a result of substantially

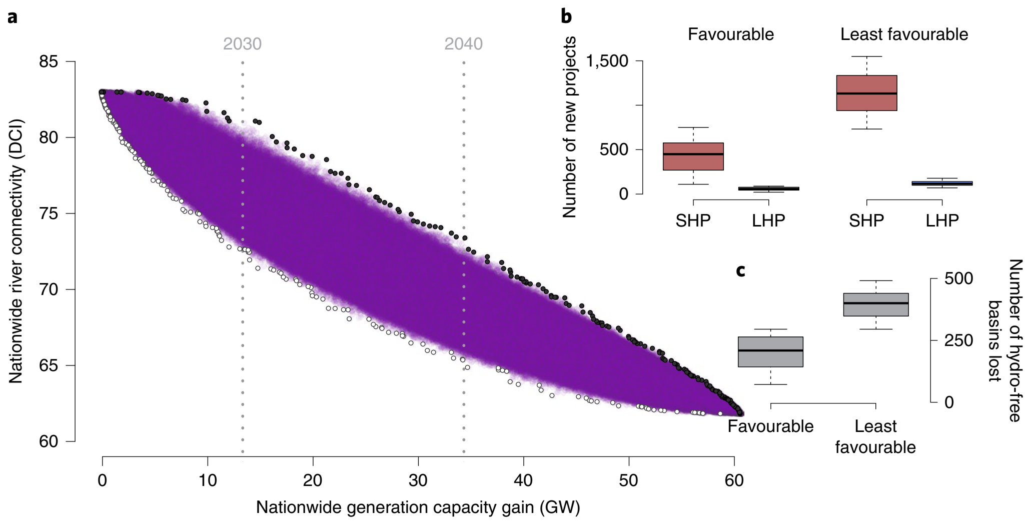

Fig. 6 | Future projections of nationwide river connectivity. a, Future projections of nationwide river connectivity (average DCI across all 1,216 basins) and total additional generation capacity (on the basis of a 2018 baseline) for 4.3 million bootstrap samples (circles) from the 2,268 planned dams in Brazil. The vertical dotted lines delineate the projected additional power need of Brazil by the decade of 2030–2040. The colours of the circles indicate the favourable (black), least-favourable (white) and remaining (purple) dam portfolios, which were computed using a Pareto frontier operator. **b**,**c**, The number of new SHP and LHP projects to be built (**b**) and the number of basins that will no longer be free of hydropower (**c**) in the favourable and least-favourable dam portfolios located within the 2030–2040 projected power demand. Boxplots represent the median (centre line), first and third quantiles (box) and 1.5 times the interquantile range (whiskers).

less SHP and LHP construction to achieve the same gains in energy capacity, yet a full accounting of the social, economic and geopolitical dimensions of different dam portfolios is a critical next step[43,44]. In addition to assessing the effects of dam construction on river connectivity, downstream hydrological and physical impacts vary among different dams and should also be incorporated into any decision-making process. Finally, SHPs are still rarely considered in assessments of the cumulative ecological effects of future hydropower despite their global proliferation[5]. For example, 40% of the recent cumulative impact assessments (CIAs) for hydropower in Brazilian basins completely ignore SHPs[12]; this should be addressed in any future reforms of energy policy.

Managing rivers for multiple sustainable benefits requires integrating scientific, social and policy perspectives into operational decision frameworks[24,45]. This study challenges nationwide policies for SHP development in Brazil that consistently assume their low potential for causing environmental impacts and generally ignore their cumulative ecological effects. We found that the expansion of SHPs poses a persistent and emerging threat to the connectivity of Brazilian rivers, resulting in important negative consequences for the conservation of migratory fish. In this regard, we demonstrate that strategic planning on the basis of trade-off analysis can provide critical guidance for new construction to meet energy needs while ensuring the smallest loss of river connectivity. However, the actual implementation of comprehensive strategic planning is challenging owing to the decentralized nature of SHP development and licensing, which are typically regulated at the state level. One possible solution is strengthening basin-level CIAs—a powerful policy that is required before licensing and that is already mandatory, albeit poorly regulated, for SHPs[12,46,47]. Coordinated efforts between the SHP industry, local stakeholders, social organizations and state/federal agencies can help to inform CIAs by adjusting them to the social, economic and environmental realities of the region.

Considering the spatial complexity of fish migrations and the socioeconomic importance of inland fisheries in Brazil, the current mechanism for hydropower siting is unsatisfactory from a socio-ecological perspective[46,48], and it needs scientifically sound and more-transparent environmental criteria. For example, although none of the SHPs of the Juruena River (Amazon Basin) are inside the boundaries of the Enawene Nawe lands, they have been reported to block fish migrations and cause declines in fish stocks that this indigenous group relies heavily on[41]. It is also important to highlight that national-level prescriptions of hydropower siting are unable to track all of the site-level social, economic and environmental repercussions of dam construction, and local impact assessments and public consultations are indispensable even for SHPs. Improving strategic planning of hydropower development with environmentally informed criteria, together with policy incentives to diversify renewable energy sources (for example, solar and wind), are potential avenues to be explored[49], and should minimize the adverse ecological effects of dam construction in tropical rivers.

Methods

Dam distributions and attributes. Our analysis combines hydrographic data with the spatial location of hydropower dams to identify fragmented river networks and quantify river connectivity across Brazil. We used the HydroSHEDS and HydroBASINS global hydrographic mapping products[50,51], which contain 1.1×10^6 river reaches draining in and to Brazil, and polygons delimiting river basins at ten spatial levels of organization. We next retrieved a comprehensive national dataset of hydropower plants from the repository of the Brazilian energy agency ANEEL[52]. This dataset contains 3,795 plants with associated attributes, including size category (that is, large, small or mini), generation capacity, opening date and status (that is, operating, under construction, decommissioned, inventory or licensing stage).

River connectivity in this study is an attribute of a river basin[22]. A 'river reach' is defined as a cartographic unit, represented by the line segment between two neighbouring confluences. A 'river fragment' is a subset of a basin's network (that is, a set of fully connected reaches) that becomes disconnected from the rest of the network after the construction of a barrier (dam). We conducted our analysis for level-eight basins (which contain on average 731 km^2 and 314 km of rivers per basin), corresponding to the scale of hydropower planning and natural resource management that accounts for the scales of migration of most freshwater fish species in Brazil[35]. River networks in coastal basins with two or more disconnected networks flowing directly to the ocean were analysed separately (as sub-basins) to ensure fully connected networks.

Brazilian regulations classify hydropower dams as 'small' if their generation capacity is <30 MW and they impound reservoirs with surface areas of <13 km^2; 'mini' when generation capacity is <1 MW; and all other dams are labelled 'large'[5]. These classifications are arbitrary choices that are not supported by scientific evidence—both small and mini dams receive licensing exemptions. We therefore combined them into a single category of SHPs. We assumed that all dams in operation in 2018 represent the current scenario, and all dams under construction or in different stages of licensing or inventory (as of September 2019) represent the projected future scenario. The future scenario reflects a time period from the present day to mid-century (around 2050) during which all of these dams were assumed to be built[53]. However, the timeline and the actual number of dams that will be constructed may change (that is, it can be greater or smaller) depending on future policies, governance and other local factors.

A series of spatial editing steps was performed on the hydropower plant dataset to ensure that it was accurately linked to the HydroSHEDS river network. This included the deletion of duplicate spatial records (for the purpose of this study, hydropower plants within 300 m of each other, retaining the plants with the largest generation capacity) and the automatic snapping of plants within 200 m of the network to the nearest river reach. Plants beyond 200 m of the river network were manually repositioned on the basis of visual reference to high-resolution imagery and to the Brazilian national cartographic dataset from IBGE[54]. Plants were discarded from the analysis in the rare occasion that they appeared to be disconnected from the main river network. Finally, we also ensured the positional accuracy of all LHPs and inspected plants of which the reported drainage area differed by more than 25% from the river reach in which they were located, or of which the power generation capacity appeared to be high compared with the annual discharge of the reach. For the 3,193 (out of 3,514) current and future plants for which the geographical coordinates of the dam were available, the final position of the adjusted point was only 239 m (median = 138 m) away, on average, from the reported location of the dam. Following these steps, our analysis included 3,063 SHPs (1,032 current and 2,031 future) and 451 LHPs (214 current and 237 future).

Migratory fish species. Although dams have been reported to modify habitats and limit dispersal and gene flow for fish species with a wide range of life histories[30,55], we opted to focus on migratory species due to their higher vulnerability to river fragmentation and their socioeconomic importance[15,17,20]. We classified the 3,130 species of freshwater fish that are formally registered in Brazil as either migratory or non-migratory on the basis of whether they demonstrate some level of longitudinal migrations in rivers to access feeding areas or to complete reproduction (that is, upstream and downstream migrations along the main channel). Species of which the migrations are restricted to lateral movements into floodplains were excluded[35]. Unfortunately, basic knowledge on natural history and migratory behaviour is lacking for most fish species[56]. We therefore compiled a list of taxonomic groups (family and genus levels) reported as longitudinally migratory in South America[35], and extrapolated our definition of potentially migratory to individual species that belong to these groups, resulting in an initial list of 505 migratory species. This strategy is supported by strong associations between dispersal ability and morphological characteristics (for example, body size and fecundity), and phylogenetic conservatism in parent–offspring dispersal distance reported in the literature[57,58]. This initial list was subsequently reviewed by two expert ichthyologists in Brazil (personal communication by J. Zuanon and R. Reis), resulting in a final list of 365 species that are highly likely to be migratory (Supplementary Table 1). Of these species, 24 are classified as vulnerable, threatened, endangered or critically endangered on the national Red List based on IUCN criteria[34], and 24 are considered to be species of highest commercial and recreational value—species with annual yields of more than 10,000 kg and/or considered to be important for sport fishing in Brazil[20,59,60]. Point datasets of occurrence records for 335 species were acquired from the environmental agency ICMBio[34]. Species occurrence data were then intersected with all river basins that have or will have at least one hydropower dam, resulting in a basin-level distribution range for 191 migratory fish species.

Quantifying river connectivity. The DCI is a metric of river connectivity that reflects the probability that a mobile organism (fish) can move between two randomly selected points from a network[22]. DCI ranges from 100 (that is, a completely free-flowing basin with no barriers) to 0, and can be calculated for any size of stream network. The DCI equations can be adjusted according to the movement behaviour of the fish species[22]. Here we adopted the DCI_p developed for potamodromous fish—the guild of migratory fishes that complete their life cycle and, therefore, migratory movement exclusively in freshwater habitats[61], which we assumed are equally likely to move upstream or downstream. More specifically DCI_p represents the stream length-weighted average connectivity among all fragment pairs within the network, where each barrier is assigned a permeability value that represents the probability of a given fish passing through the barrier, and connectivity is the joint probability that a fish can move between two fragments given the permeability of all barriers between the fragments. The DCI_p is expressed as:

$$\mathrm{DCI_p} = \sum_{i=1}^{n}\sum_{j=1}^{n} p^{m_{ij}} \frac{l_i}{L}\frac{l_j}{L} \times 100$$

where n is the number of stream fragments in the network (that is, equal to the number of barriers plus one), and the indexes i and j designate the fragment identities from 1 to n. The lengths of the fragments i and j are represented by l_i and l_j, which are weighted by the total length of the network (L). $p^{m_{ij}}$ expresses the connectivity between the fragment pairs, where p is the two-way permeability of every barrier and m_{ij} is the number of barriers between the fragment pairs i and j. We used 10% as the permeability for all dams (that is $p = 0.1$), which is a conservative estimate informed by research reporting very low efficiencies of fish passage structures. For example, the efficiency of upstream passage was reported to be between 0.7% and 21% for non-salmonid fishes and for dams located in South American rivers[62,63].

We attributed the same permeability to SHPs and LHPs due to the lack of evidence relating the performance of fish passage structures and size-categories of hydropower[64]. Although smaller dams may seem to be easier to pass over or bypass compared with LHPs, there are three main reasons why this is unlikely. First, size classifications on the basis of hydropower generation capacity do not necessarily reflect ecologically relevant attributes (for example, dam height, reservoir area and flow alteration) that constrain fish movement[5,65,66]. For example, many SHPs operate as diversion schemes, dewatering long main channel sections and ultimately limiting fish movements in addition to the dams[5,67]. Second, a high proportion of fish passages associated with SHPs have been reported to have critical structural and maintenance problems that completely eliminate their functionality[64]. Third, SHPs have less rigorous requirements for environmental mitigation compared with LHPs, which means that the presence of fish passages and their monitoring and regular maintenance are also less probable[5]. To examine the effect of the permeability of SHPs and LHPs on our results, we ran a sensitivity analysis that revealed no major changes in the findings. Notably, SHPs still accounted for most projected future DCI losses even when increasing the permeability of SHPs to 50% and decreasing the permeability of LHPs to 0% (Supplementary Fig. 7). Our analysis did not include potential natural barriers to fish migration, such as waterfalls, due to the lack of a comprehensive national dataset and to the high diversity of migratory fish in the analysis—species respond differently to different types of natural barriers[68].

DCI analysis was conducted for scenarios containing SHPs alone, LHPs alone and both dam types combined in each of two time periods (current and future). Trends in DCI over the past century were also examined according to the opening dates of 1,211 (97%) dams from our dataset. We opted to separately explore scenarios of the existence of just SHPs or just LHPs because the contribution of each dam barrier to the basin-level DCI is non-additive. We therefore ran two separate DCI analyses, each of them containing a single dam type but ignoring the presence of the other (SHPs versus LHPs). We report DCI results (for example, nationwide average) for only the 1,216 Brazilian basins that have or will have at least one hydropower dam in the future (Figs. 1–4). These basins represent 10% of all basins in Brazil (11,911 basins level 8 from HydroBASINS) and 15% of the total Brazilian river network by length. The remaining basins that are less attractive for hydropower (DCI = 100) were excluded from the analysis.

Selecting hydropower dam portfolios. We estimated the unique contribution of each planned dam to basin-level DCI using a permutation analysis that calculated the difference between DCIs when a given dam is present and absent in each basin, repeated for all of the possible combinations of future 2,031 SHPs and 237 LHPs across the country. The overall contribution of each planned dam was summarized as the mean and the range of marginal DCI loss when present in the basin, across all of the possible future dam development scenarios in that basin. In a second step, we examined 4.3 million future dam portfolios with respect to total nationwide generation capacity and average basin-level DCI. Each portfolio represents a random selection of a future number of dams that were sampled from the pool of 2,268 planned dams. Analysing all of the possible portfolios (all of the permutations of dam sites in each basin) would necessitate a massive computational effort, as the number of all portfolios equals 5.4×10^{682}, calculated as 2^n, where n is the number of planned dams. We determined the set of favourable and least-favourable dam portfolios (that is, the Pareto frontier) that best and worst traded-off gains in hydropower generation capacity with losses in nationwide river connectivity. We computed the Pareto frontier for future favourable and least-favourable scenarios using the function psel of the R package rpref. This function uses a top-k skyline operator to identify Pareto-optimal sets of data that meet the preference queries of an objective[69]—which, in our case, are the dam portfolios that maximize the capacity gains and minimize the connectivity losses for the favourable portfolios and the opposite for the least-favourable portfolios. Future demands for hydropower generation capacity were defined as 120–141 GW from 2030 to 2040 according to an international report that estimated energy policy scenarios[70]. Although it does not include all possible dam portfolios, this simulation exercise successfully captured the overall Pareto frontier that was expected from an optimization analysis of all of the possible solutions. This was supported by an overall stabilization of the Pareto front solutions beyond a threshold of a few million simulated portfolios (Supplementary Fig. 8). It is important to note that our analysis did not account for connection access to the national grid, generation efficiency, construction and maintenance costs, and many other social and economic factors that may have important roles in the final decision-making. However, we assessed whether inefficiencies that are inherently associated with hydropower generation (such as due to local hydrology and turbine efficiency) could represent a source of bias to our results. We reproduced our analysis with estimates of capacity factors (that is, proportion of the capacity that is actually translated into energy generation) for SHPs and LHPs. The results remained consistent with our analysis using generation capacity, as the capacity factors of SHPs and LHPs do not substantially differ on average (an explanation of the methods is provided in Supplementary Methods and the results are provided in Supplementary Figs. 9 and 10).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All of the analyses were based on governmental (ANEEL, IBGE, ICMBio) or open source datasets, such as HydroSHEDS and HydroBASINS. All references are included in the text. A repository with a research compendium including non-reproduceable data sources, intermediate products, scripts and guidance to reproduce the results is available at Figshare (https://figshare.com/s/5ba67b7f58ccc812ae70). The output data generated by our analysis are provided in Supplementary Tables 1–6.

Code availability

The code used to analyse the data and generate figures are available at GitHub (https://github.com/messamat/BrazilDCI_Python and https://github.com/messamat/BrazilDCI_R).

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Author contributions

T.B.A.C. and J.D.O. designed the study, and all of the authors led the writing. T.B.A.C. and M.L.M. worked on the data acquisition, processing and analysis in R, and M.L.M. coded the spatial analysis in Python.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	All the analysis were based on governmental (ANEEL, IBGE, ICMBio) or open source datasets like HydroSHEDS and HydroBASINS. No analytical software was used to collect the data.
Data analysis	Codes developed during the analysis are available in the links https://github.com/messamat/BrazilDCI_Python and https://github.com/messamat/BrazilDCI_R. We run all the analysis using R (version 3.6.1), Python (version 2.7) and ArcGIS (version 10.5).

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All the analysis were based on governmental (ANEEL, IBGE, ICMBio) or open source datasets like HydroSHEDS and HydroBASINS. All references are included in the text. Supplementary tables include the output data generated by our analysis.

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Study description	This study is a comprehensive assessment of the cumulative river fragmentation by Small Hydropower Plants (SHPs) in Brazil. First, we compare the cumulative effects of current and projected-future SHPs and LHPs on network connectivity of Brazilian rivers (1,216 river basins that have or will have at least one hydropower dam in the future were used in this comparison). Second, we quantify the resulting range-wide loss of connectivity for 191 migratory fish species (i.e. connectivity loss in basins where these 191 species have already been recorded). Third, we explore trade-offs between gains in energy capacity and loss in river connectivity to inform strategic planning for the development of new hydropower constructions in the country (one million bootstrap samples were taken from the pool of all possible combinations of future dams).
Research sample	All the analysis were based on governmental (ANEEL, IBGE, ICMBio) or open source datasets like HydroSHEDS and HydroBASINS. These datasets contain 1.1 x 10^6 river reaches draining in and to Brazil, 3,795 present-day and planned hydropower dams, and distribution records of 335 migratory fish species (191 species occur in basins that have or will have at least one dam in the future).
Sampling strategy	All Brazilian basins and dams were included in the analysis. 4.3 million bootstrap samples were taken to identify differences between optimal and least-optimal future dam portfolios (2,268 future dams present in the analysis).
Data collection	All the analysis were based on governmental (ANEEL, IBGE, ICMBio) or open source datasets like HydroSHEDS and HydroBASINS.
Timing and spatial scale	Analysis are based on the spatial position of present-day (built by 2018) and projected-future (to be built by circa 2050) hydropower dams inside the Brazilian borders.
Data exclusions	Dams were discarded from the analysis in the rare occasion when they were duplicated or appeared to be disconnected from the main river network (snapping to the river network). A total of 3,514 dams (out of 3,795 from the original dataset) were included in the analysis.
Reproducibility	A series of code reviews and optimizations have been repeated by the authors in different computers since September of 2019, and the results have been consistent
Randomization	We examined one million future dam portfolios with respect to total nation-wide generation capacity and average basin-level DCI. Each portfolio represents a random selection of a future number of dams that were sampled from the pool of 2,266 planned dams
Blinding	Data was acquired from governmental and open source datasets. Scenarios (SHPs Vs LHPs; present-day Vs projected-future), spatial scales, migratory species and dams permeability were defined a priori. A sensitivity analysis and an adjusted DCI function (DCIi; a metric or river connectivity loss) were employed to test the consistency of the results (Supplementary figures).

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging