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A baseline for assessing the ecological integrity of Western Amazon rivers

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Amazon freshwater systems influence global hydroclimatic patterns, host unparalleled biological diversity, and support unique social-ecological systems. Rivers of the Western Amazon underpin this global importance with an outsized, underrecognized role at the Amazon Basin scale. Here we examined the status of several components—hydrology, sediments, freshwater fish biodiversity, and longitudinal river connectivity—that support the ecological integrity of Western Amazon rivers and their linkage to the greater Amazon Basin. Streamflow is largely driven by precipitation and the region supplies nearly all sediments delivered by the Amazon River to the Atlantic Ocean. The Western Amazon harbors 74% of the ichthyofauna of the entire Amazon Basin. Existing dams and road crossings have disrupted longitudinal river connectivity on several rivers. We estimated that 47.8 million people reside in the Amazon Basin, with more than half (58%) inhabiting the Western Amazon. This study helps establish a baseline for tracking change in Western Amazon river ecosystems.

Amazonian forests have long been globally recognized for their extraordinary biodiversity, massive stores of carbon, influence on climatic patterns, and links to human life, livelihood, and culture[1–4]. More recent efforts have heralded the global importance of the Amazon's freshwater systems, which—similar to Amazonian forests—also influence global hydroclimatic patterns, host unparalleled biological diversity, store, export and transform vast quantities of carbon, and underpin a unique social-ecological system[5–7]. For example, the Amazon River contributes an average flow of 6,600 km^3/year to the Atlantic Ocean, making it the single largest source of continental discharge on Earth, responsible for about 20% of the global freshwater flow from rivers to oceans[8,9]. Additionally, huge amounts of water, upwards of 6,400 km^3/year, are exported from the Amazon Basin to the atmosphere via aerial rivers and moisture recycling, processes that drive rainfall patterns across much of South America[8,10]. Amazon freshwaters harbor an estimated 15–20% of scientifically documented global freshwater fish diversity with >2800 described species[11–13]. Human life, culture, economy, and livelihood for the human populations of the Amazon, including >350 distinct Indigenous groups and growing urban populations, are intimately connected to freshwaters, which provide thoroughfares for transportation and water supply, provide protein and income from fisheries, and have inspired countless origin stories for Indigenous groups[14,15].

The increasing recognition of the global importance of Amazon freshwaters has begun to translate into newfound enthusiasm for their conservation within and outside of the basin[5,16,17]. Related efforts have called attention to the need to pursue new legal and institutional frameworks that offer durable protection for rivers, which typically flow outside of, or form the borders of, protected areas in the Amazon[18]. A recent analysis of river connectivity across the Amazon Basin illustrated that a majority of rivers are still considered free-flowing from source to outlet, meaning that they do not have dams or other physical barriers[19]. This estimate includes most short (10–100 km) and medium (100–500 km) rivers, as well as 79% of long (500–1000 km) and 63% of very long (>1000 km) rivers[19]. Much remains to be conserved across the Amazon in terms of free-flowing river corridors, perhaps even more than in other large tropical river basins[19,20].

Within this larger discussion of the global importance of Amazon freshwaters and calls for their conservation, the Western Amazon region plays an outsized–yet often unrecognized–role. Many large-scale studies of the Amazon typically focus only on the Brazilian portion of the basin, leading to scientific bias and under-recognition of the contributions of the Western Amazon. However, the eastern flank of the Andes is one of the regions of highest annual precipitation across the entire Amazon Basin[21]. Rivers draining that region—including the Caquetá-Japurá, Putumayo-Içá,

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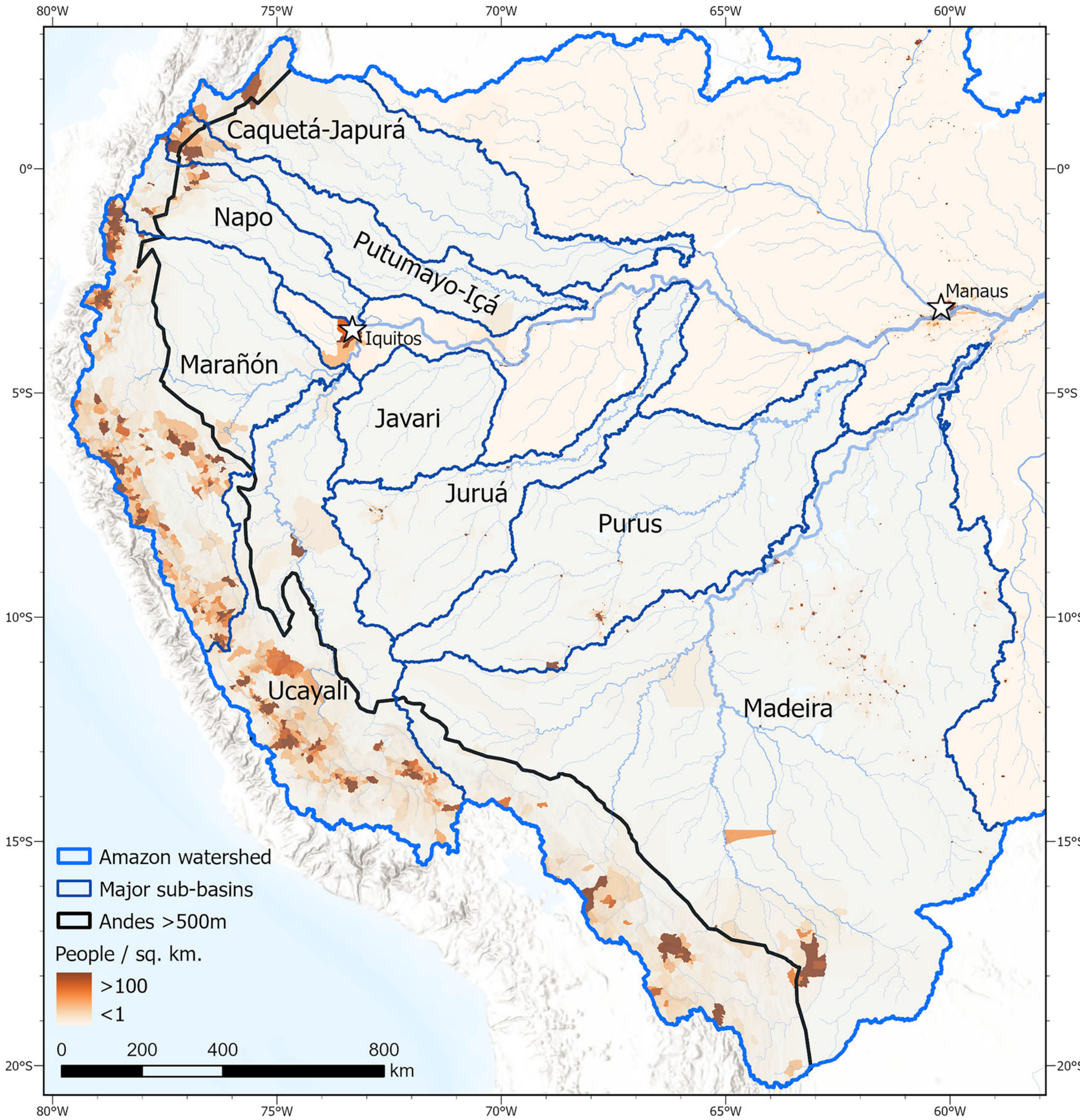

Fig. 1 | Major river basins and human population densities in the Western Amazon. Data source: Gridded Population of the World, version 4[77].

Napo, Marañon, Ucayali, and the Madre de Dios, Beni, and Mamoré rivers of the upper Madeira Basin (Fig. 1)—export massive amounts of water, sediment, and nutrients to the Amazon lowlands and Atlantic Ocean. Their contributions account for an estimated 40% of the Amazon Basin's total water and >90% of the sediment outflow to the Atlantic Ocean[8,22]. These numbers are extraordinary, given that the Andean Amazon—defined here as areas >500 meters above sea level—only accounts for ~13% of the Amazon Basin area yet is the source for most of this sediment[23]. Further, Andean tributaries deliver much higher amounts of nitrogen and phosphorus to the mainstem than do lowland tributaries of the mainstem and export important amounts of carbon in many forms[7,23–26].

Environmental gradients, largely driven by elevation and climate, have created an array of habitats for freshwater, amphibian, and terrestrial species along the eastern flank of the Andes[27,28]. This region is recognized as one of the most significant global centers of species diversity across numerous taxonomic groups[1,29,30]. At the scale of the Amazon Basin, the Western Amazon stands out as an important region for freshwater biodiversity, as measured by aquatic invertebrates and by freshwater fish species richness and endemism[31–33]. Recent studies have suggested that the sub-basins of the Western Amazon have higher fish species richness than the more eastern or downstream sub-basins[33]. This is an atypical pattern in riverine environments, where fish species richness tends to increase in a downstream direction[34]. Further examination of this pattern considering the paleogeographic history of South America has posited that the Western Amazon could be the central geographic area of diversification for much of the modern Amazonian ichthyofauna[29].

Rivers of the Western Amazon harbor specialized fish assemblages with high levels of endemism, shaped by natural biogeographic barriers and strong elevational gradients, often greater than 5000 meters, that characterize the region[35–37]. Many fishes are highly specialized to the fast-flowing waters of tropical montane rivers of the Andes, displaying morphological adaptations[38], as well as behavioral and reproductive adaptations[39] to these environments. Additionally, migratory species are an integral component of Amazonian freshwater ecosystems, and Western Amazon rivers are known migration corridors for fish species that move from the lowlands to the Andean piedmont and foothills for spawning[40–42].

The Western Amazon also has been subjected to varied and often irreversible processes of transformation over the past century. Agricultural expansion accelerated in many Western Amazon basins in the first half of the 20th century, followed by expansion of urban areas, which continues today[43]. Deforestation, gold mining, and infrastructure development such as roads and hydropower dams, especially in middle and high elevation areas

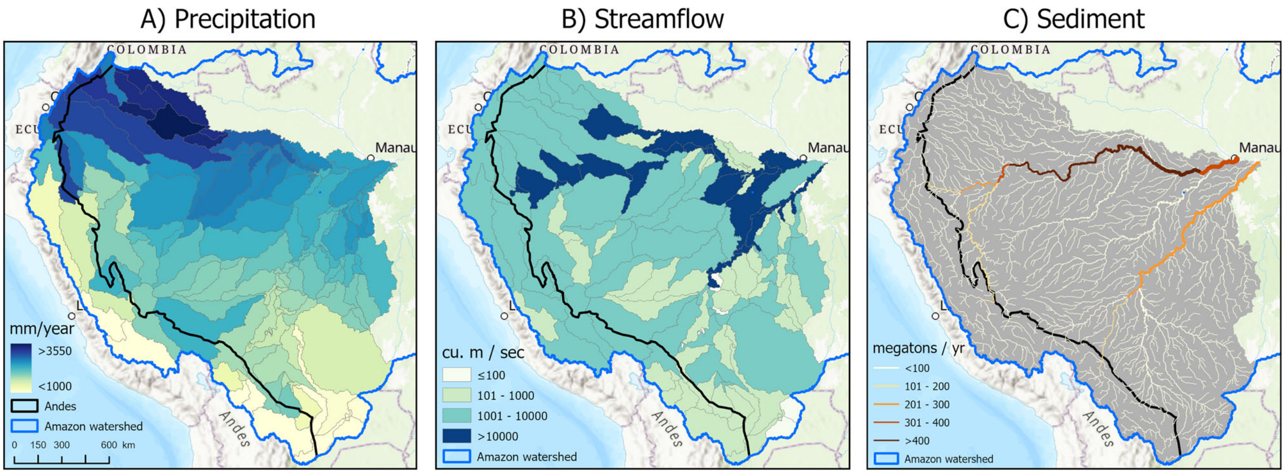

Fig. 2 | Average annual precipitation, streamflow, and sediment discharge for the Western Amazon. **A** Average annual precipitation (mm/year) in Western Amazon river basins at Basin Level 6 (BL6[46]). The Andes mountains are outlined in thick black. Precipitation is generally highest in northern tributaries and decreases moving southeast. Precipitation is also generally less in the high Andes compared to lower elevations. **B** Average annual streamflow discharge (m^3/s, log scale) of Western Amazon river basins at BL6 for the period 1990-2009. Streamflow contributions from Andean basins vary, although northern basins generally have higher streamflows than southern basins. These patterns are consistent with precipitation patterns, reflecting that streamflow in the Western Amazon is largely driven by precipitation patterns. **C** Average annual sediment discharge (tons/year) for Western Amazon streams in the period 1992–2009. Sediment discharges from rivers of Andean origin are significantly higher than discharges from rivers of non-Andean origin.

of Andean-Amazon River basins, have further altered the landscapes and river corridors of that region, especially during the present century[3,44,45]. Despite these changes, there are still many largely unimpeded major river corridors that connect the high Andes to downstream areas of the lowland Amazon and Atlantic Ocean, and therefore much opportunity remains to conserve these critical pathways[45].

In this study, we aimed to highlight the importance of the Western Amazon as a fundamental component of overall freshwater conservation for the Amazon Basin and to provide a baseline for tracking change to its rivers over time. As described above, existing research has already shown that the Andes mountains exert strong regulatory controls on the geomorphological and ecological characteristics of the downstream Amazon River, its floodplains, and its estuary, as facilitated by connectivity along riverine pathways. Additionally, the Western Amazon is a global center of biological and cultural diversity that is tightly linked to connected river ecosystems. Within this context, we asked: what is the status of key components that underpin the ecological integrity of Western Amazon rivers and their linkages to the larger Amazon basin? Using an interdisciplinary approach, we assessed (i) patterns related to hydrology and sediments; (ii) freshwater fish biodiversity; and (iii) river connectivity along longitudinal pathways. Additionally, we estimated human populations and mapped their location in the Western Amazon.

Results

Hydrology and sediments

The results for precipitation, streamflow, and sediments data were generally consistent with patterns documented in previous studies (e.g.[21,22]). However, their organization at Basin Level 6[46] allows for understanding and tracking of variability at scales relevant to local and regional watershed management. For baseline results, mean annual precipitation (Fig. 2) and streamflow patterns indicated that streamflow of Western Amazon sub-basins was largely driven by precipitation. For the period of record (1981-2020), precipitation was generally highest in the northern tributaries of the Western Amazon (Caquetá-Japura, Putumayo-Içá, and Napo basins) and decreased moving southeast (Beni and Mamoré sub-basins of the upper Madeira). Precipitation was also generally lower in high Andean sub-basins (>3500 m) compared to lower elevations (1000 m)[47]. Mean annual streamflow patterns were generally consistent with these precipitation patterns, with the Amazon mainstem towards the north having higher overall contributions compared to the Madeira mainstem in the south. Southern sub-basins with precipitation hotspots, such as the upper Ucayali basin and upper Madre de Dios (Madeira Basin), also had relatively high streamflow.

Mean annual suspended sediment yield patterns indicated that the Andes supply essentially all the sediment discharged by the Amazon River (Fig. 2). The Marañón, Ucayali, and Madeira (Madre de Dios, Beni, and Mamoré sub-basins) were the dominant sediment sources compared to the Caquetá-Japura, Putumayo-Içá, and Napo basins as well as to the Juruá, Javari, and Purus basins.

Freshwater biota

A total of 1,868 fish species, representing 74% of the total Amazon's ichthyofauna, have been scientifically documented from the Western Amazon region (Fig. 3 [12,13]). The Madeira basin has the highest number of recorded species and the Javari and Juruá have the lowest numbers from this region. Considering the basin sizes, the Napo basin has the highest density of species while the Madeira has the lowest. The number of endemic species from the Amazon found within the Western Amazon basins (i.e., Amazon scale endemics) mirrors species richness patterns (Fig. 3). However, the patterns differ when considering only the number of endemic species with respect to each Western Amazon basin (i.e., basin scale endemics). The Madeira basin has the highest number and density of unique species followed by the Marañón and Ucayali (Fig. 3).

At the extent of the entire Amazon basin, migratory fish species richness peaks along the lower mainstems of the Amazon and Madeira rivers and decreases towards the Amazon headwaters, which are mainly used as spawning grounds, whereas the floodplains are the feeding and growth habitats of those species. Our results highlight that the mainstems of all the major basins that originate in the Western Amazon are inhabited by at least 76 longitudinal migratory fish species. This estimate encompasses approximately 88% of fish species known to perform longitudinal migrations in the Amazon Basin[42]. Some longitudinal migratory species—fishes that move tens, hundreds, or even thousands of kilometers along longitudinal pathways often for reproductive or feeding migrations—potentially reach areas over 500 m.a.s.l., notably in the Caquetá-Japura, Putumayo-Içá, Napo, Marañón, Ucayali, and Madeira basins (Fig. 4).

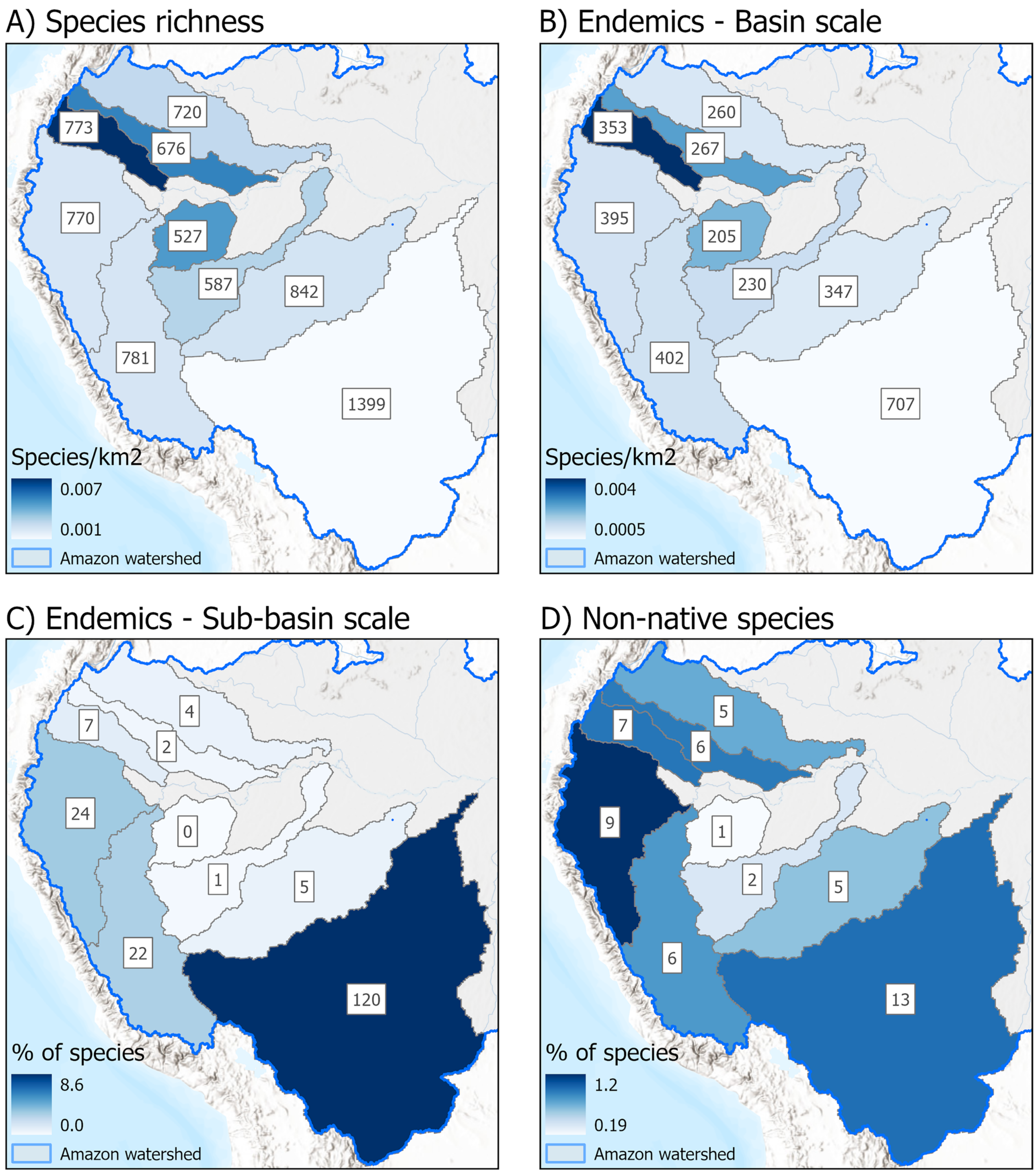

Fig. 3 | Freshwater fish diversity patterns in the Western Amazon. Patterns shown include species richness (**A**), number of endemic species at the Amazon basin (**B**) and Western Amazon sub-basin scales (**C**), and non-native species (**D**). The total number of species are indicated in the white labels, while the basin color represents the number of species per km^2 (**A, B**) and the percentage of species with regards to the total of the Western Amazon sub-basin (**C, D**). Western Amazon sub-basins from north to south: Caquetá-Japurá, Putumayo-Içá, Napo, Marañón, Ucayali, Javari, Juruá, Purus, and Madeira (also see Fig. 1).

Longitudinal river connectivity

Our analysis indicated notable presence of road crossings and dams on Western Amazon rivers. We documented 13,734 road crossings in Western Amazon basins that potentially impose barriers to longitudinal connectivity on small streams (Table 1). Our analysis also documented that 396 (45.6%) of 888 dams registered for the entire Amazon were located within Western Amazon basins. As of 2020, 142 of these were existing hydropower dams on rivers of the Western Amazon (Table 1), and an additional 51 dams were built for purposes other than hydropower (most of them in the Ucayali Basin). We also documented 203 proposed dams at various stages of planning, ranging from initial conceptualization of potential sites to advanced projects already under licensing. At the time of analysis, dams were most heavily concentrated in the Madeira, Marañón, Ucayali, and Napo River basins (Table 1); only the Putumayo-Içá, Javari, and Juruá lacked existing dams or current plans for proposed projects.

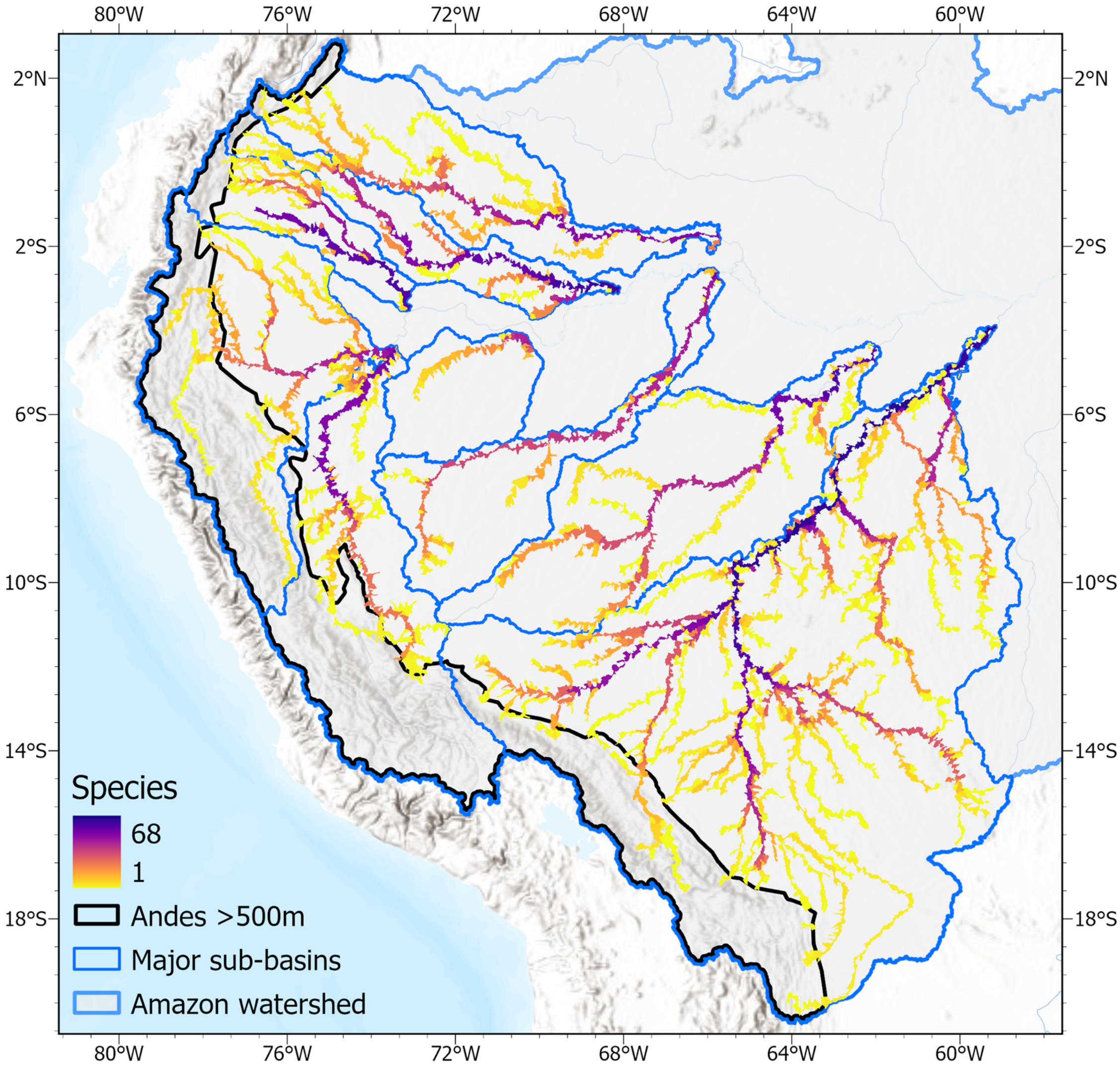

Fig. 4 | Western Amazon rivers are migration corridors for migratory fishes. Species richness of longitudinal migratory fish species is shown along the major rivers in the Western Amazon. Blue lines delineate basins of the Western Amazon, and black lines delineate Andean regions above 500 m elevation.

River connectivity estimates based on the Dendritic Connectivity Index (DCI) indicated large disparities among the nine basins we assessed because of the presence of dams (Fig. 5, Supplementary Table 1). The Madeira and Marañón have experienced most of the intrabasin connectivity loss, having current levels of connectivity of 51% and 70%, respectively. With 203 proposed dams, intrabasin connectivity is expected to continue decreasing in the future, with most severe reductions in connectivity expected in the Madeira, Marañón and Ucayali (Fig. 5). For interbasin connectivity, owing to the two large dams built upstream of the city of Porto Velho, Brazil, the Madeira has a connectivity level of just 31%. However, besides the Madeira, all other Western Amazon basins have current connectivity levels above 83%. These numbers reflect the current distribution of dams in the Napo, Marañón and Ucayali basins, where most existing dams are located on tributaries and high elevation rivers distant from the basins' mouths.

Human populations

Our analyses indicated that the Western Amazon region is one of the most densely populated areas of the Amazon Basin. We estimated that 47.8 million people inhabit the Amazon Basin (Table 2[48]), including the Tocantins. Human populations are concentrated in two main areas: in the Andean region, particularly at middle and high elevations where large cities are found along major river courses, or at the convergence of major rivers in the Amazon lowlands (Fig. 1). The Western Amazon is home to 58% of the Amazon Basin's human population, about 27.7 million people. Of the Western Amazon sub-basins, the Madeira has the highest human population (10.6 million; Table 2), which is concentrated in large cities like Cochabamba and Santa Cruz de la Sierra, Bolivia, and Porto Velho, Brazil. The Marañón sub-basin also has a relatively high human population, estimated at 7.4 million people and much of it contained in urban areas of the high Andes such as the Latacunga, Ambato, and Riobamba metropolitan areas of Ecuador and around the cities of Tarapoto, Tingo Maria, and Yurimaguas in Perú.

Discussion

The Western Amazon is distinguished by its enormous influence on distant Amazonian lowland and Atlantic coastal areas and its role as a global center of biological and cultural diversity. Yet, it is increasingly susceptible to various forces of change. Our study established a baseline assessment of hydrology and sediment patterns, freshwater biodiversity, longitudinal river connectivity, and human populations in the Western Amazon. These components influence the composition, structure, and function of ecosystems in the Western Amazon, the greater Amazonian lowlands, and coastal Atlantic Ocean.

Our results highlighted precipitation as a major driver of streamflow patterns in Western Amazon rivers, particularly in the Andean foothills, piedmont, and lowland regions, where some of the highest levels of annual precipitation across the Amazon occur. In the high Andes, where streamflow and precipitation are lower, glaciers may have significant contribution to local streamflow, particularly during dry periods and in the Puna ecosystems of Perú and Bolivia[49]; this contribution rapidly decreases moving downstream and is minimal outside of the Andes. Páramos, high elevation grasslands and wetland ecosystems of the northern Andean Cordillera also play an important role in the local water cycle at high elevations, historically releasing steady streamflow to streams and rivers. However, streamflow contributions from the páramo, like those of glaciers, decrease in importance moving downstream, where rainfall dominates[50]. Our results for sediment patterns also highlighted the importance of Andean piedmont and lower elevation areas as primary sediment sources. Andean headwater streams can have the highest sediment loads, yet they are usually restricted to relatively short and sporadic periods (e.g., storm events)[22]. Most of the annual sediment load of the Amazon River is derived from lower elevation Andean streams (roughly <500 m.a.s.l.) that unite multiple headwater tributaries, flow downstream, and directly deposit and exchange sediments with lowland Amazon floodplains[51,52].

Our results provide further evidence of the importance of the Western Amazon as a hotspot for freshwater fish biodiversity within the Amazon Basin[33,35], showing that three-quarters of the Amazon's entire ichthyofauna inhabits Western Amazon sub-basins. Nevertheless, exotic species pose an underappreciated threat to Amazonian fish assemblages and freshwater ecosystems[53]. Their introductions may be facilitated by interaction between aquaculture for food production, river fragmentation, and climate change[33,54,55]. Exotic species could threaten the integrity of the Western Amazon basin by potentially outcompeting or preying on native aquatic species.

Our study also highlighted the role of Western Amazon rivers as critical migration corridors for at least 76 species of migratory fishes. Whereas previous studies have documented continental-scale fish migrations that occur along main river channels and the foothills of the Andes[40], our results show that some longitudinal migratory species are found in the Andes above 500 m asl, potentially reflecting the occurrence of migrations at higher elevations in many basins, such as in the Madeira River[56,57]. The magnitude of these migrations over the large spatial and diverse taxonomic levels on which they occur needs further research[42].

Table 1 | Hydropower dams and road crossings in the Western Amazon

Sub-basin	Existing dams		Planned dams		Road-crossings
	LHP	SHP	LHP	SHP	
Caquetá-Japurá	0	0	1	0	1221
Putumayo-Içá	0	0	0	0	553
Napo	4	5	9	13	577
Marañón	11	24	55	27	2675
Ucayali	9	9	30	7	2542
Javari	0	0	0	0	0
Juruá	0	0	0	0	184
Purus	0	0	0	5	432
Madeira	18	62	26	30	5550
Total	42	100	121	82	13,734

Existing and proposed hydropower dams and estimated number of road-crossings by sub-basin across the Western Amazon. LHP large hydropower (>30 MW), SHP small hydropower (<30 MW). Non-hydropower dams are not presented in the table.

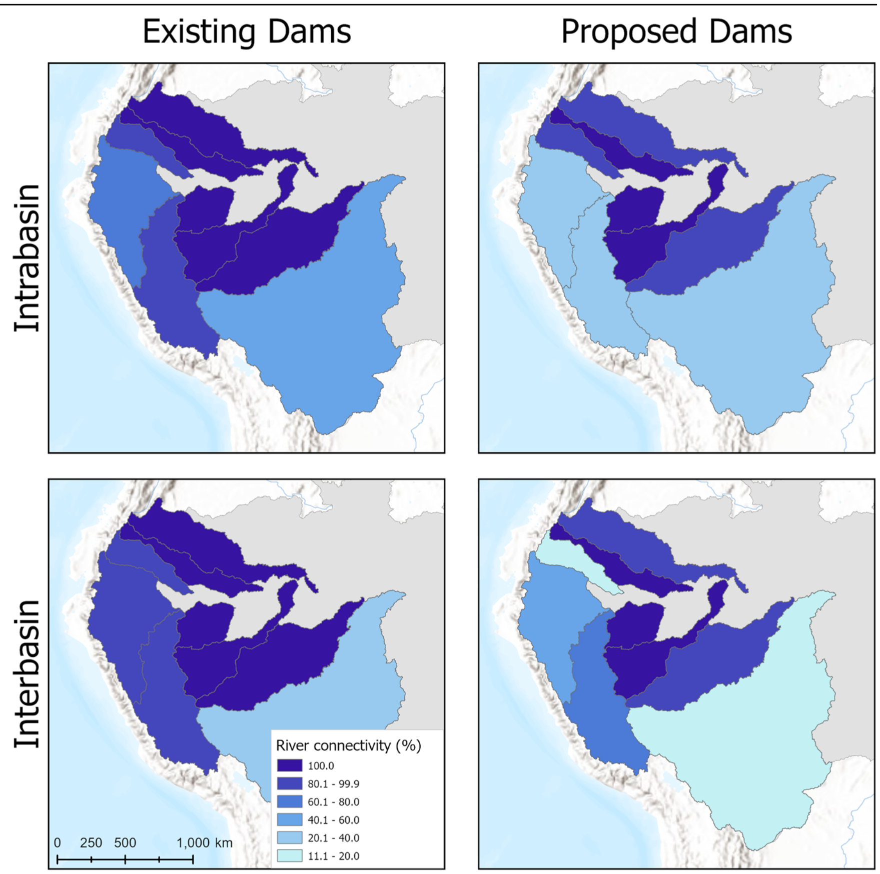

Fig. 5 | Longitudinal river connectivity for Western Amazon Rivers. Longitudinal river connectivity estimates (DCI) expressed in percentage for Western Amazon sub-basins under two scenarios: present-day, existing dams (left panels) and projected-future, proposed dams (right panels). 100% connectivity indicates an unfragmented river network. Estimates of connectivity are separated by intrabasin and interbasin reference scenarios. Large hydropower dams are the most significant overall drivers of losses in longitudinal river connectivity. Small hydropower dams are prevalent in high Andean areas of the Marañón, Napo, and Madeira sub-basins. Western Amazon sub-basins from north to south: Caquetá-Japurá, Putumayo-Içá, Napo, Marañón, Ucayali, Javari, Juruá, Purus, and Madeira (also see Fig. 1).

Table 2 | Western Amazon sub-basins

Sub-basin	Area (sq. km)	% area	Human population	Pop. density (people/ sq km)
Putumayo - Içá	118,066	1.7%	1,022,437	8.66
Caquetá - Japurá	253,696	3.7%	933,074	3.68
Javari	107,674	1.6%	42,962	0.40
Juruá	188,239	2.7%	429,612	2.28
Madeira	1,315,029	19.1%	10,561,209	8.03
Marañón	362,388	5.3%	7,418,589	20.47
Napo	99,928	1.5%	688,894	6.89
Purus	369,103	5.4%	894,916	2.42
Ucayali	353,085	5.1%	5,760,126	16.31
Western Amazon SubTotal	3,167,208	46.0%	27,751,818	8.76
Amazon Basin	6,889,956	100%	47,806,301	6.94

Area of Western Amazon sub-basins and percentage of the entire Amazon Basin each represents. Estimated human population in the Amazon watershed and Western Amazon sub-basins, calculated using version 4 of the Gridded Population of the World[77].

For longitudinal river connectivity, our results indicated decades of change from dam development and road construction across the Western Amazon. Many existing dams, constructed in the present century, are located at middle or high elevations on tributary rivers. Therefore, much of the longitudinal river connectivity along mainstem rivers that connect the Andes and the lowland Amazon remains intact. Although our analysis focused on existing dams, we predict that the future expansion of hydropower dams to larger mainstem rivers of the Napo, Marañón and Ucayali basins could result in major disruptions of interbasin connectivity (Fig. 5). For instance, just one single dam proposed for the lower Napo mainstem in Perú (Mazan, 150 MW) could drive a reduction of 86% in interbasin connectivity given its proximity to the Napo River's confluence with the Amazon River. Future infrastructure projects would disrupt the downstream export of water, sediments, and nutrients from the Andes to the lowland Amazon and coastal Atlantic and would hinder the upstream movement of migratory fishes from the lowlands to the Andean piedmont and foothills[8,42]. These projections underscore the need for basin-scale and multiobjective optimization approaches for planning future infrastructure developments[58].

Our study offered an insightful look at human population in the Amazon by river basin and showed that the Western Amazon is home to more than half (58%) of the entire human population of the Amazon (47.8 million). Often, calculations and visualizations of human population follow political boundaries rather than hydrologic boundaries. Our results illustrated the importance of the Madeira (10.6 million), Marañon (7.4 million), and Ucayali (5.7 million) in harboring large human populations at the scale of the entire Amazon Basin. Our results could be combined with other datasets to explore demographic patterns by river basin now and into the future, given that human populations in the Western Amazon relate to rivers in diverse ways. For example, rivers are a source of water for agricultural and industrial uses, particularly in the drier regions of the high Andes and in urban centers, respectively (e.g. [59,60]). Domestic needs for water throughout much of the region are met by rivers as well[61]. Limited wastewater and solid waste management around urban areas has led to the use of rivers for dumping untreated sewage, industrial effluent, and trash (e.g. [62]).

Despite these challenges, rivers continue to hold important economic and cultural values for riparian human populations in the Western Amazon. Especially in piedmont and lowland areas, freshwater fishes provide a major source of nutrition and income[63], and rivers are often the main or only thoroughfare for transportation and communication between human settlements[64]. Culturally, the cosmovision of numerous Indigenous groups in the Western Amazon emphasizes the spiritual significance of rivers and their diverse inhabitants[15]. The daily, seasonal, and annual rhythms of human life in the Western Amazon–in terms of livelihood activities, festivals and celebrations, and social relations–are interlinked with the inherent fluctuations of flows, or the rhythmicity, of rivers[15]. Stewarding these human connections to rivers is an important consideration under future scenarios of change in the Amazon.

Additional efforts to document change for rivers in the Western Amazon could consider the additive or interactive effects of hydrology and sediments, freshwater biodiversity, river connectivity, and human population growth, something not thoroughly considered in our analysis. Further analyses could also incorporate new factors, such as carbon export and transport by Western Amazon rivers, and consider other taxonomic groups with connections to freshwater for greater understanding of biodiversity in general. Additionally, each of the Western Amazon sub-basins is itself a large river system by global standards and therefore comprises diverse geographic and ecological contexts. Further examination of smaller areas within the larger Western Amazon sub-basins will be necessary for a spatially diverse, more comprehensive approach to establishing baselines and tracking change over time. This level of detailed study of each of the sub-basins was beyond the scope of our study, as we sought to provide a regional perspective on the entire Western Amazon. Whereas our study relied on published datasets, future analyses could include empirical data and ground-truthing of existing information for specific geographic locations where data resolution may be coarse. Further, more detailed study of stakeholders' interests, concerns, and engagement would provide important information for considering things like tradeoffs between economic, environmental, and societal goals, especially considering proposed infrastructure developments, such as new roads and dams.

Maintaining freshwater ecosystem connectivity of the Western Amazon is an essential component of conservation strategies at the scale of the entire Amazon Basin. Given development trends in the Western Amazon, especially the continued expansion of urban areas and large-scale infrastructure, it is critical to establish a spatial baseline necessary to monitor and mitigate the impacts of future changes. At the time of this paper, many Western Amazon rivers still flow freely, offering a historic opportunity for freshwater conservation in the Amazon. Further, riparian human communities are a common feature along river corridors and play an important role in their protection. Maintaining Amazon's freshwater systems and their connectivity into the future will require new approaches that extend beyond the typical model of conservation applied in the Amazon over the past few decades, which has focused on terrestrial protected areas that sometimes exclude people[18]. A suggested approach is the recognition of Western Amazon river corridors as objects of conservation and establishment of transnational fluvial reserves that protect and remove certain rivers from consideration as locations for large infrastructure projects in the future. There is a need for conservation models like fluvial reserves that guarantee fish movement along river corridors, protect the seasonal variability of river flows, can be co-designed with riparian human communities, and recognize the role of freshwaters as integrators and influencers of social-ecological systems throughout the Amazon Basin.

Methods

Study site

We defined Western Amazon river basins as Andean-origin rivers that drain toward the Amazon mainstem, but not including the mainstem. These include all the Caquetá-Japurá, Putumayo-Içá, Napo, Marañón, Ucayali, and Madeira basins. Also included are the Juruá, Purus, and Javari basins, whose headwaters arise in a low hilly region just west of the Andes that is associated with the Fitzcarrald Arch (Fig. 1 [65]). Many of these rivers, particularly those with headwaters in the high Andes Mountains, are characterized by strong elevational and climatic gradients and frequent disturbance regimes linked to hydrologic events, landslides, and rainfall erosion[27].

Hydrology and sediments

Our analyses for hydrology and sediments focused on annual precipitation, streamflow, and suspended sediment yields. For all analyses, we used HydroSHEDS and HydroBASINS hydrographic mapping products[66,67] to delimit rivers and their basins across the Western Amazon. For precipitation, we used the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data[68]) dataset for years 1981 to 2020 (40 years). For streamflow, we used outputs from a fully coupled hydrologic-hydrodynamics model, MGB (Modelo Hidrológico de Grandes Bacias, Large-Scale Hydrological Model), that was simulated over the entire continent of South America[69]. Streamflow data for each sub-basin reflected estimated magnitudes at the outlet of each respective sub-basin. For suspended sediment, we used outputs from a continental sediment model (MGB-SED)[70] that was driven by the MGB streamflow data[69]. The streamflow data was for years 1990 to 2009 (20 years) and sediment data for years 1992 to 2009 (18 years), and each were modeled at a daily time step.

Freshwater biota

We mapped freshwater biodiversity in the Western Amazon using (1) fish richness and endemism patterns and (2) distribution of migratory fish species and routes. For both purposes, we primarily used the AmazonFish database[12] and Dagosta & de Pinna[11], which have the most updated information on the distribution of more than 2800 described Amazonian fish species. To map fish migration patterns, we estimated the ranges of migratory species that perform longitudinal migrations in the Amazon and for which occurrence data were available in the Western Amazon (full species list available in Supplementary Table 2). We used a robust, scalable, and easy-to-implement geometric approach based on minimum spanning trees to estimate species ranges in freshwater network systems[19,71].

Longitudinal river connectivity

To assess the status of longitudinal river connectivity, our analysis considered two major human-induced alterations to rivers: road crossings and hydropower dams. These two types of infrastructure have been described as the primary drivers of river connectivity losses across much of the Amazon[1,9,45,72,73]. For road crossings, the number and location of road crossings were estimated for Western Amazon basins by intersecting roads and the HydroSHEDS hydrographic map product[67]. Spatial data about roads was retrieved from the RAISG network database[14], which includes linear projections and associated information obtained from individual-country transportation agencies for built road infrastructure. We selected streams spanning from first to fourth order from the HydroSHEDS network and retained point-intersections with roads in the GIS environment. For hydropower dams, we compiled a dataset for the Amazon Basin based on the most updated and reliable spatial data available for the Brazilian Amazon[74] and for the Andean-Amazon[45]. The dataset included a total of 888 point records representing unique dam sites (326 existing and 565 proposed) for the whole Amazon basin.

We applied the Dendritic Connectivity Index (DCI) to examine the effects of dams on longitudinal connectivity on Western Amazon rivers[75]. This index reflects the probability that an aquatic organism, such as a fish, can move between two randomly selected spatial reference points in a river network, expressed in a percentage scale. We used HydroSHEDS and HydroBASINS hydrographic mapping products[66,67] to delimit rivers and their basins across the Western Amazon. Two types of spatial reference points were used to adjust DCI equations, which reflected the relative effects of barriers on overall basin connectivity (intrabasin) or from ascending movements (interbasin)[75,76]. Both DCI values were calculated for present-day and projected future scenarios of dam construction (Supplementary Information). Although road crossings have a collective potential to promote stream fragmentation and increased bank erosion, information available did not allow us to assume that all crossings represent actual barriers for water flow and animal movement (e.g., cases where bridges cross a stream without being a barrier like a culvert). Because of the lack of validation in the field, we opted to remove road crossings from the analysis of connectivity.

Human population

To map human population across the Amazon Basin and to estimate populations per basin, we used the GIS-ready dataset Gridded Population of the World (version 4 [77]). For basins we used the Amazon GIS-Based River Basin Framework[46,78]. Analyses were done using ArcGIS Pro version 3.2.

Data availability

All data used in this study were publicly available. The sources are described and referenced in the Methods and in the Supplementary Information.

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Competing interests
The authors declare no competing interests.

Additional information
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