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Title: Assessing global river connectivity to map the world's remaining free-flowing rivers

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Abstract:

Rivers are the 'arteries of the Earth', critical to sustaining aquatic ecosystems and many societal and economic services. However, many benefits, like sediment supply to deltas, fisheries and biodiversity, require free-flowing river networks, while others, like water supply and hydropower, require technical infrastructure and dams that disrupt river connectivity and impede associated ecosystem processes. Safeguarding and restoring free-flowing rivers is a grand management challenge, made more urgent by accelerated hydropower development and an unprecedented decline in freshwater biodiversity. Here, we define free-flowing rivers in terms of connectivity, assess the status of 12 million km of rivers globally, and identify those that remain free-flowing along their full length. Our results show that very long (>1,000 km) rivers are the most threatened with only 36% remaining free-flowing and only 23% free-flowing and connected to the ocean. These results reinforce the urgent imperative for concerted global and national strategies to maintain and restore free-flowing rivers around the world.

One Sentence Summary:

Built infrastructure has reduced global river connectivity to alarming levels, mandating better basin management and planning to maintain and restore free-flowing rivers.

Main Text:

Rivers are one of humanity's great sources of environmental health and economic wealth. For millennia, rivers have served as centers for civilization and, in modern economies, they provide water to people, industry and agriculture, sustain transportation corridors, and drive electricity generation (*1*). These services generally require built infrastructure, and society has addressed this demand by constructing an estimated 2.8 Mio dams (with reservoir areas >0.1 ha; *2*) and regulating over 500,000 km of rivers for navigation and transport (*3, 4*). However, this vast infrastructure has impacted the health of freshwater ecosystems, their biodiversity and the associated ecosystem services (*5*), caused primarily by the loss of natural connectivity that sustains many of the fundamental processes and functions of rivers (*6*).

Built infrastructure can affect riverine connectivity either directly through the impeding effect of the structure itself, or indirectly through alterations to the hydrological, thermal and sediment regimes. The biophysical vitality of rivers depends largely on the natural flow regime (*7*), regulating connectivity by providing the aquatic medium through which organic and inorganic matter and species move along the river and access adjacent habitats. Changes in connectivity can manifest across four dimensions, where the movement of organisms, sediments, organic matter and nutrients can be altered longitudinally (upstream to downstream), laterally (main channel to floodplains), vertically (between surface and ground water), and through time (*8*). These changes affect riparian and aquatic biota, ecosystem processes and related services (*9, 10*). Indeed, floodplains are among the most productive and diverse riverine ecosystems globally, and their disconnection from the river channel alters aquatic and terrestrial biodiversity and ecosystem services such as natural flood retention, nutrient removal, and flood-recession agriculture (*11*). Built river infrastructure has also been linked to declines in terrestrial species (*12, 13*), and sediment capture by dams is a primary cause of widespread geomorphic change and the shrinking of river deltas worldwide (*14, 15*). While advances in the socio-economic valuation of river connectivity have begun – e.g., inland fisheries provide the equivalent of all dietary animal protein for 158 Mio people globally (*16*) – more comprehensive and detailed studies are needed (*17*).

Acknowledging the importance of river connectivity, a decade ago the Brisbane Declaration (*18*) called for the identification and conservation of "a global network of free-flowing rivers", and in 2015 the world's governments committed to "protect and restore water-related ecosystems" under the United Nations' Sustainable Development Goals (Target 6.6). Yet the continued and increasing declines in river connectivity and associated ecosystem services remain a global challenge facing nations and affecting those who depend on healthy rivers. The rising demands for energy, water supply and flood management are increasingly calling for engineering solutions such as the construction of dams and other built infrastructure to be constructed at a rapid pace. Indeed, more than 3700 hydropower dams (>1 MW) are currently planned or under construction worldwide (*19*). Asia is a hot spot for dam construction with over 15 GW capacity added in 2016; and the Balkans and Amazon are also facing major booms in hydropower construction (*20, 21*). Furthermore, several countries are either planning or building enormous inland water transfer and navigation schemes (e.g., India, China, Brazil), which require massive dredging, channelization and levee construction (*22*).

Paramount to the conservation of free-flowing rivers is the availability of a comprehensive global information system that allows monitoring the actual state and future trends of riverine connectivity. Previously, fragmentation and flow regulation by dams were quantified worldwide at nested spatial scales (*23, 24*), providing snapshot assessments of connectivity. Recent improvements in the accessibility and resolution of global hydrologic data have allowed for more spatially detailed and comprehensive assessments of rivers, including the development of advanced metrics of fragmentation at the river reach scale (*25*). Building on these advancements, we provide a high-resolution and replicable global assessment of the location and extent of remaining free-flowing rivers (FFRs).

We define FFRs as rivers where natural aquatic ecosystem functions and services are largely unaffected by changes to fluvial connectivity allowing an unobstructed exchange of material, species and energy within the river system and surrounding landscapes. We further specify that the longitudinal (river channel), lateral (floodplain), vertical (groundwater and atmosphere) and temporal components of fluvial connectivity can be compromised by (a) infrastructure or impoundments in the river channel, along riparian zones, or in adjacent floodplains; (b) by hydrological alterations of river flow due to water abstractions or regulation; and (c) by changes to water quality that lead to ecological barrier effects caused by pollution or alterations in water temperature.

Following this definition, we identified five main pressure factors that affect different components of river connectivity and for which global data were available: (a) river fragmentation; (b) flow regulation; (c) water consumption; (d) road construction; and (e) urbanization. For each pressure factor, we compiled and constructed proxy indicators using global data and numerical model outputs. The analysis was conducted using a high-resolution (500 m) river network model that comprises about 8.5 Mio individual river reaches, with an average length of 4.2 km (*26*). In this paper, we define a *river reach* as a line segment between two confluences; a *river stretch* as two or more contiguous reaches but not the entire river; and a *river* as the aggregation of river reaches that form a single-threaded, contiguous flow path from headwater source to river outlet (i.e., the river's mouth at the ocean; an inland depression; or a confluence with a larger river). Guided by published literature and expert judgement, we applied a set of weights within a multi-criteria model to derive a novel, integrated Connectivity Status Index (CSI) that quantifies connectivity ranging from 0% to 100% for every individual river reach. Finally, we defined free-flowing rivers as those with a CSI above 95% over their entire length from source to river outlet, and then quantified their extent and mapped their distribution.

Global river connectivity at the reach scale: About half of all river reaches globally show diminished connectivity to some degree (CSI <100%; Fig. 1) with almost 10% of global river reaches (more than 1.1 Mio km) having a CSI value below 95%, indicating major losses of connectivity. Large contiguous river networks with intact natural connectivity (CSI = 100%) only remain in remote regions of the far North, within the Amazon Basin, and to a lesser degree in the Congo Basin.

Dams and reservoirs and their up- and downstream propagation of fragmentation and flow regulation are the leading contributors to major connectivity loss in global river reaches (Fig. 2). The fragmentation effect of dams is the dominant pressure factor in almost half of river reaches below the 95% threshold, followed by flow regulation effects. Water use, roads, and urbanization are strong correlates of CSI in rivers where dams are less widespread, such as consumptive water use in highly irrigated regions of India and China and dense urbanization in western Europe.

Remaining free-flowing rivers: By number, 64% of the world's longest rivers (>1,000 km) are no longer free-flowing (Table 1), representing 41% of global river volume (*sensu 23*). Long FFRs (>500km) are largely absent from the mainland United States, Mexico, Europe and the Middle East, as well as parts of India, southern Africa, southern South America, China and much of Southeast Asia and southern Australia (Fig. 3). The remaining long FFRs are restricted to the northern parts of North America and Eurasia, the Amazon and Orinoco Basins in South America, the Congo Basin in Africa, and to only a few areas in Southeast Asia, including the Irrawaddy and Salween Basins. For example, nine of the ten longest FFRs in South America are located within the Amazon Basin (External Databases S1).

Free-flowing rivers still connected to the ocean exhibit similar patterns; those that remain are found predominantly in the Arctic, in a few basins in Southeast Asia, and in the neo- and Afro-tropics. Source to sea connections have been severed in 77% of very long rivers (>1,000 km), and in 56% of long rivers (500–1,000 km).

Although many rivers are not free-flowing due to one or more impacted reaches (CSI <95%) along their course, some of them contain significant stretches that maintain high levels of connectivity. Among non-FFRs worldwide, a total of 622,000 km of river reaches can be classified as having a "good connectivity status" (CSI ≥95%), with 84 contiguous river stretches longer than 500 km, including substantial parts of the Brahmaputra (India/Bangladesh), Orinoco (Venezuela and Colombia), and Amur (Russia) Rivers (Fig. 3 and Table S1).

Validation, limitations, and scalability: Our global results suggest that river connectivity increases with decreasing river length. A total of 51%, 77% and 96% of rivers with lengths of 500–1000 km, 100–500 km, and 10–100 km, respectively, are identified as free-flowing (Table 1). This pattern can partially be attributed to the biased global distribution of small rivers which occur preferentially in the remote, water-rich, and relatively unaffected regions of the Amazon and Congo Basins. However, it is also important to carefully interpret the status of short rivers recognizing the limitations of underlying global datasets of pressure factors, particularly the lack of georeferenced smaller dams and diversions. Our study considered only large and medium sized dams, while countless smaller dams exist worldwide (*2*). Therefore, we expect that numerous short rivers are false positives and are classified as free-flowing despite impeding infrastructure projects which are not currently included in global datasets, such as the case in highly developed regions of Europe or North America. This fundamental data limitation underscores the need for governments and global institutions to fund the acquisition of high-resolution geographic water infrastructure data.

To develop and test our global approach, we conducted three case studies for large, medium, and small river basins (Tapajos, Brazil; Luangwa, Zambia; and headwaters of Ganges, India) where we piloted the methodology with additional local information. Empirical application of the methods in these regions helped to improve the identification of FFRs worldwide, in particular for short rivers. The results from these case studies indicate that our global methodology is robust for long rivers and is scalable to be replicated in regional and local studies if additional data are available.

The CSI and the FFR methodology presented here provide metrics for evaluating river connectivity as one of the fundamental components of ecosystem health (*27-29*). However, a comprehensive evaluation of river health would include other components such as water quality, land use, and an assessment of biological and ecological conditions that also shape ecosystem integrity (*30*). Thus, the river connectivity metrics provided here could be included as one component in comprehensive investigations of river health.

A global conservation challenge: With their numbers reduced to 36%, long FFRs (>1000 km) have become increasingly rare and remain prevalent only in remote areas of the world that are difficult to be exploited economically (e.g., Arctic), too large to be developed by current technology (although this is changing), or in less developed regions (e.g., Congo). Of special concern is the loss of connectivity of long rivers to the sea as they play a critical role in the exchange of water, nutrients, sediments and species with deltas, estuaries, and the ocean. Long FFRs deliver disproportionately high levels of ecosystem services, most notably inland and floodplain fisheries, sediment transport, and biodiversity (*15, 16, 21, 31*). For example, the last two remaining long FFRs in Southeast Asia—the Irrawaddy and Salween Rivers—are known as a critical source of protein from inland fisheries, providing more than 1.2 Mio tons of catch annually (*32*), and their flow regimes maintain extensive floodplain agriculture in a region inhabited by more than 30 Mio people.

Given the importance of FFRs, plans to rapidly develop new infrastructure in basins around the world should be accompanied by comprehensive strategic and transboundary impact assessments and should consider alternative development pathways to minimize harmful consequences (*33, 34*). In a world of accelerating hydropower development (*35*) and a shift to low carbon economies (*36*), forward-looking system-scale approaches to energy and hydropower planning, including multi-objective trade-off analyses, are required to minimize loss of river functions while meeting energy targets (*37, 38*). Our results, data and methods can play a critical role in such efforts, prioritizing rivers with high conservation value for protection, and optimizing decision making for infrastructure development.

In addition, our framework could be applied to target restoration interventions towards locations or methods that improve connectivity most effectively (*39*). New and existing algorithms could assist in restoring or retrofitting affected river systems, such as by minimizing flow regulation, the strategic removal of dams or levees, or designing and constructing effective fish passages that would deliver the greatest return in terms of increasing CSI (*40*) as well as offering some assurance of effectiveness (*41*).

The Connectivity Status Index (CSI) by itself is a novel metric that provides a range of opportunities for future application. It is applicable to any river reach, unlike previous efforts that focused primarily on the exclusive assessment of dam impacts or provided metrics only at the large basin scale. Although the role of dams in river fragmentation and flow regulation has shown to be prevalent (Fig. 2), the CSI also accounts for other factors that disrupt the longitudinal, lateral, vertical and temporal aspects of connectivity. Based on the CSI, the presented new and integrated method for quantifying connectivity allows assessing the status of rivers across multiple scales, from individual river reaches to aggregated rivers, with discharges spanning more than seven orders of magnitude.

Global environmental change, including climate and land use change (*42*), will further increase the pressure on rivers and their connectivity through alterations in flow patterns and intermittency, modifications in the frequency, magnitude and timing of droughts or floods, and changes to water quality and biological communities. FFRs may serve to increase the resiliency of aquatic and riparian ecosystems under these added stresses, as they provide open pathways for species movement to suitable habitats in other parts of the basin in response to rising temperatures or other changing conditions (*43*). To maintain this resilience, infrastructure planning and decision making should include scenarios of future environmental change in development plans.

The international community has committed to the protection and restoration of rivers under Agenda 2030 for Sustainable Development, which calls on all countries to track, at a national scale, the spatial extent and condition of water-related ecosystems (*44*). This study delivers methods and data necessary for defining the baseline and for tracking changes in the connectivity status of rivers. It has, for the first time, comprehensively identified the extent and distribution of remaining FFRs globally, highlighting that action is needed to protect or restore these threatened systems.

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Figures and Tables:

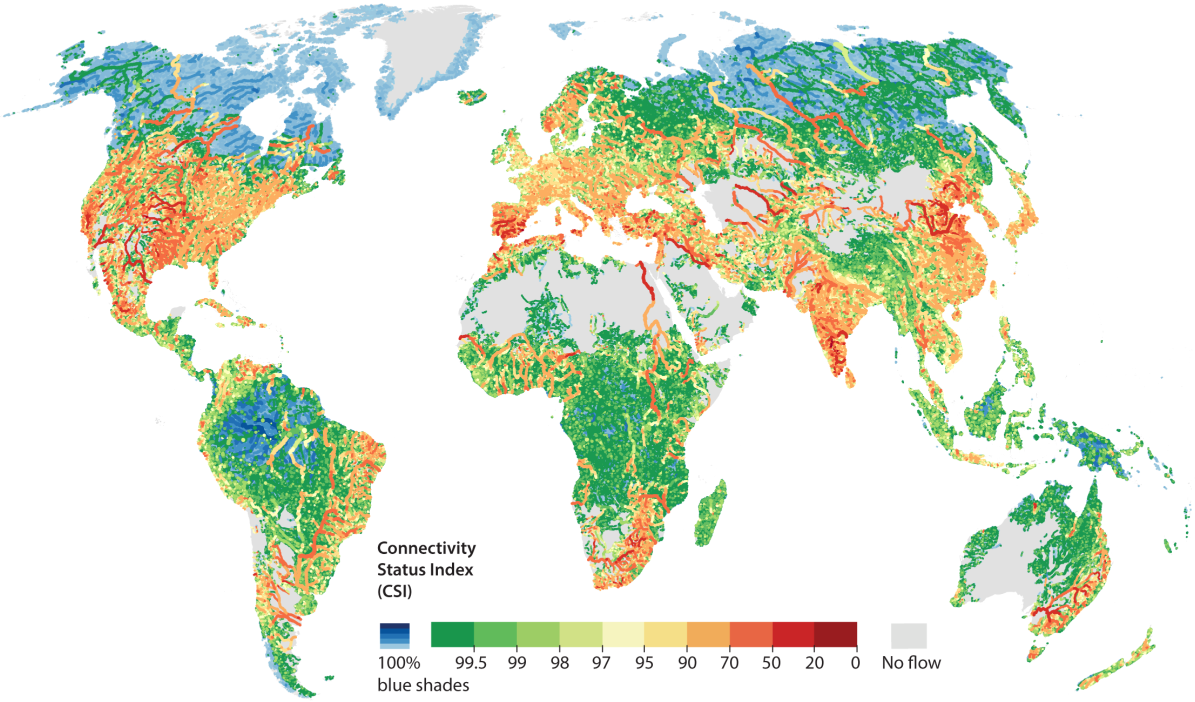

Fig. 1. Global Connectivity Status Index (CSI) of the world's rivers. Of all river reaches in the database, 48.5% (by number) are impaired by diminished river connectivity to various degrees (CSI <100%).

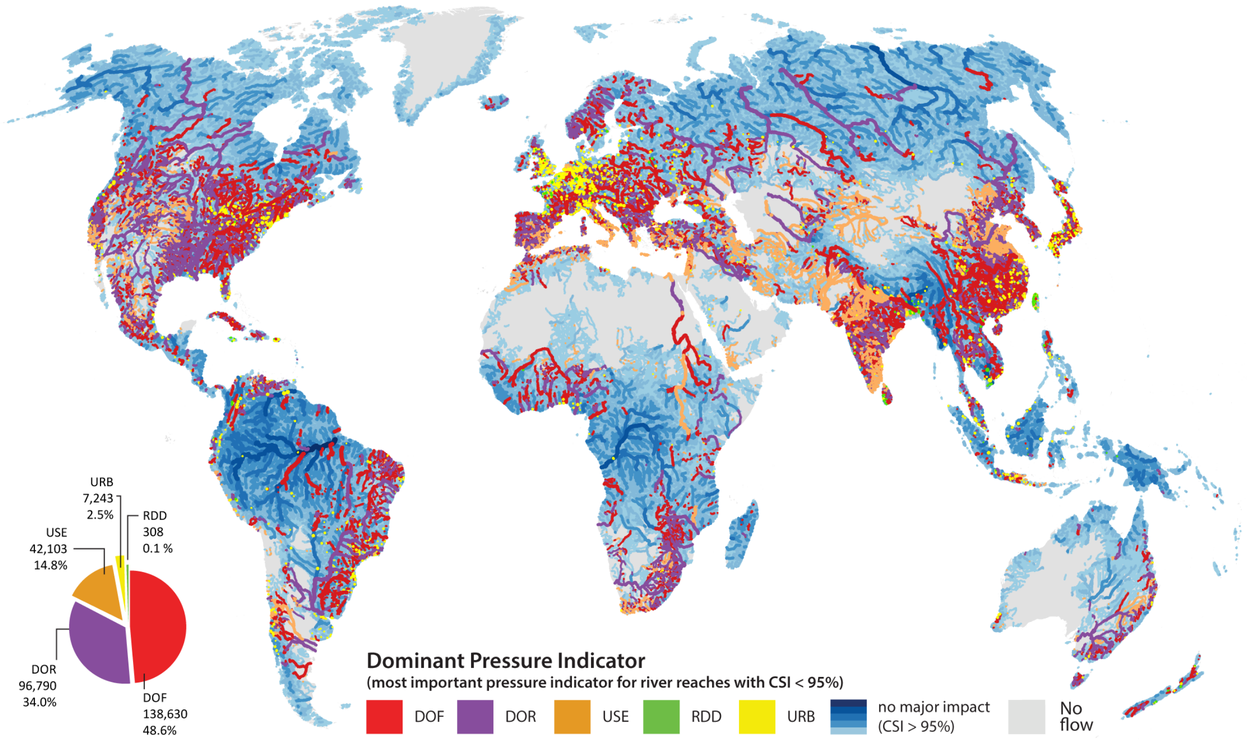

Fig. 2. Dominant pressure indicator for global river reaches below the CSI threshold of 95%. The dominant pressure indicator is the factor that contributed most to the final CSI index value after applying the weighting scheme. Lower-left inset shows the number and proportion of river reaches per dominant pressure indicator. Pressure indicators include DOF = 'Degree of Fragmentation'; DOR = 'Degree of Regulation'; USE = 'Consumptive water use', RDD = 'Road density'; and URB = 'Nightlight intensity in urban areas'.

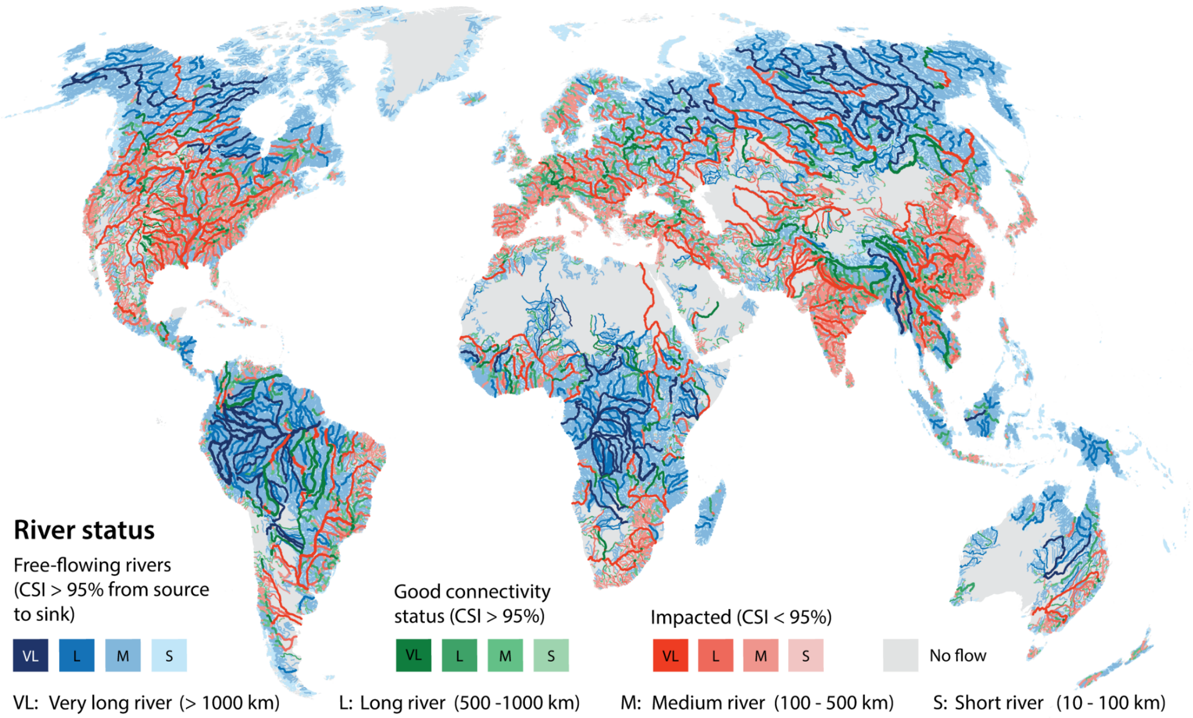

Fig. 3. Global distribution of free-flowing rivers (FFRs), contiguous river stretches with 'good connectivity status', and impacted rivers with reduced connectivity. Rivers that are not free-flowing over their entire length (i.e., partially below the CSI threshold) are divided in stretches with 'good connectivity status' (i.e., connectivity status remains above the threshold throughout stretch; green colors) and stretches where the connectivity status is below the CSI threshold (red colors). A list of FFRs longer than 500 km is given in 'External Database S1'.

Table 1: Number (a) and accumulated length (b) of free-flowing rivers and rivers connected to the ocean (c) by length category and continent.

(a) Number of free-flowing (FF) and non-free-flowing (NFF) rivers by length category and continent

	10–100 km		100–500 km		500–1000 km		>1000 km		
Continent	**FF**	**NFF**	**FF**	**NFF**	**FF**	**NFF**	**FF**	**NFF**	**Total**
Africa	34,314	599	2,616	357	120	49	26	31	38,112
Asia	67,775	5,469	3,040	1,075	97	100	21	48	77,625
Australia	26,737	442	1,005	143	33	24	3	2	28,389
Europe	25,068	2,519	1,132	845	22	76	3	22	29,687
N. America	46,174	2,076	2,237	745	43	82	11	30	51,398
S. America	78,295	1,544	2,339	438	89	54	22	23	82,804
Total	**278,363**	**12,649**	**12,369**	**3,603**	**404**	**385**	**86**	**156**	**308,015**
% of category	**96%**	**4%**	**77%**	**23%**	**51%**	**49%**	**36%**	**64%**	

(b) Accumulated length (thousand km) of free-flowing (FF) and non-free-flowing (NFF) rivers by length category and continent

	10–100 km		100–500 km		500–1000 km		>1000 km		
Continent	**FF**	**NFF**	**FF**	**NFF**	**FF**	**NFF**	**FF**	**NFF**	**Total**
Africa	1,024.0	27.1	458.1	80.0	78.0	32.8	41.0	51.8	**1,792.8**
Asia	1,874.3	182.0	517.2	209.8	64.0	68.4	38.4	103.0	**3,057.2**
Australia	624.0	16.8	168.7	29.5	23.7	16.7	4.9	4.1	**888.3**
Europe	773.7	102.8	181.3	166.9	13.8	53.0	4.4	37.4	**1,333.3**
N. America	1,351.9	81.3	362.3	146.8	28.8	55.5	14.3	57.4	**2,098.3**
S. America	1,827.6	53.9	401.1	90.6	57.1	37.5	38.8	44.2	**2550.8**
Total	**7,475.4**	**463.8**	**2,088.7**	**723.5**	**265.5**	**263.9**	**142.0**	**297.9**	**11,720.6**
% of Category	**94%**	**6%**	**74%**	**26%**	**50%**	**50%**	**32%**	**68%**	

(c) Number of free-flowing (FF) and non-free-flowing (NFF) rivers connected to the ocean by length category and continent

	10–100 km		100–500 km		500–1000 km		>1000 km		
Continent	**FF**	**NFF**	**FF**	**NFF**	**FF**	**NFF**	**FF**	**NFF**	**Total**
Africa	832	64	237	60	15	19	3	14	1,244
Asia	3,126	713	256	190	17	17	8	18	4,345
Australia	5,374	150	335	61	24	10	1	1	5,956
Europe	2,698	594	164	218	5	31	2	14	3,726
N. America	5,045	167	455	60	20	28	6	12	5,793
S. America	2,404	224	245	143	15	19	1	11	3,062
Total	**19,479**	**1,912**	**1,692**	**732**	**96**	**124**	**21**	**70**	**24,126**
% of category	**91%**	**9%**	**70%**	**30%**	**44%**	**56%**	**23%**	**77%**	

Supplementary Materials:

Materials and Methods
Supplementary Text
Figures S1-S5
Tables S1-S6
External Databases S1-S2

Supplementary Materials for

Assessing global river connectivity to map the world's remaining free-flowing rivers

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This PDF file includes:

- Materials and Methods
- Supplementary Text
- Figures S1-S5
- Tables S1-S6
- Captions for external databases S1-S2

Other Supplementary Materials for this manuscript includes the following:

External databases S1 to S2 as Excel files:
[DB_S1_Major_FFRs.xls, DB_S2_Ref_Rivers.xls]

Materials and Methods

Overview

The main methodological steps of our assessment are detailed below and depicted in Figure S1. We first developed an integrated definition of free-flowing rivers (FFR) (step 1; see Supplementary Text) according to multiple aspects of connectivity. Next, we identified five major pressure factors (step 2) that influence river connectivity according to an extensive literature review, and collated data for each factor. These pressure factors include: (a) river fragmentation; (b) flow regulation; (b) water consumption; (d) road construction; and (e) urbanization. We calculated proxy indicators (Table S2) for each factor using data from available global remote sensing products, other data compilations, or numerical model outputs such as discharge simulations. We specifically chose indicators that we expect to have substantial influence on connectivity and can be generated using robust global data sets of sufficient quality and consistency between countries and regions. All indicators were calculated for every river reach of the global river network (step 3).

Guided by literature reviews and expert judgement, we iteratively adjusted the weighting of each pressure indicator in a set of scenarios and tested different thresholds to yield a best match between the resulting FFRs and a benchmarking dataset of reported FFRs compiled from literature resources and expert input.

The final selection of weights was applied to a multi-criteria average calculation (step 4) to derive the Connectivity Status Index (CSI) for every river reach (step 5). The CSI ranges from 0% to 100%, the latter indicating full connectivity. Only river reaches with a CSI of >95% were considered as having 'good connectivity status' while river reaches below 95% were classified as impacted (step 6). Finally, river reaches were aggregated into rivers, i.e., contiguous flow paths from the source to the river outlet. If a river is above the CSI threshold of 95% over its entire length it is declared to be a FFR. Otherwise, the river as a whole is declared not free-flowing, yet it can maintain a mix of stretches with 'good connectivity status' and stretches that are impacted.

Hydrographic framework

We integrated all indicator datasets in our modeling framework using the spatial units of the HydroSHEDS database. HydroSHEDS is a hydrographic mapping product that provides river and catchment information for regional and global-scale applications in a consistent format (*26*), including catchment areas and discharge estimates. For this study, we extracted a global river network from the provided drainage direction grid at 500 m pixel resolution by defining streams as all pixels that exceed a long-term average natural discharge of 100 liters per second or an upstream catchment area of 10 km^2. We refrained from including streams below these thresholds as they are increasingly unreliable in their representation through global datasets. These selection criteria resulted in 8,477,883 individual *river reaches* (i.e., line segments between confluences) with an average length of 4.2 km (SD = 4.8 km), totaling 35.9 Mio km of river network. Each river reach is linked to a polygon of its contributing hydrological sub-catchment, with an average area of ~12 km^2.

In this paper, we define a *river reach* as a line segment between two confluences; a *river stretch* as two or more contiguous reaches but not a full river; and a *river* as an aggregation of river reaches that form a single-threaded, contiguous flowpath from headwater source to river outlet. The river outlet can represent either the river mouth at the ocean; a terminal inland depression; or the confluence with a larger river (Fig. S2). It should be noted that while we used the full river network for conducting the initial calculations, we removed all rivers from the statistical analyses and reported results that were shorter than 10 km, showed an average annual river flow of less than 1 m^3/s, or were in hot or cold deserts according to existing physiographic maps to exclude increasingly uncertain results of smaller rivers (see discussion in main text). These selection criteria resulted in 308,015 distinct rivers with a total length of 11.7 Mio km globally.

For each river reach, estimates of long-term (1971–2000) discharge averages have been derived through a geospatial downscaling procedure (*25*) from the 0.5º resolution runoff and discharge layers of the global WaterGAP model (*45, 46; v2.2 as of 2014*). WaterGAP is a well-documented and validated integrated water balance model that simulates both natural discharge (i.e., without human modifications) and anthropogenic discharge; for the latter, consumptive water use, i.e., total water abstractions minus return flows are calculated for agricultural (mostly irrigation), industrial and municipal sectors.

For all network calculations, we applied the global river routing model HydroROUT (*23*) which is built upon the HydroSHEDS database and features a nested, multi-scale model approach; advanced implementation of connectivity; and uses a novel object-oriented vector data structure in a graph-theoretical framework. HydroROUT was implemented in this study to calculate river reach level indicators, such as the Degree of Fragmentation (DOF), the Degree of Regulation (DOR), and the Connectivity Status Index (CSI) as described below.

Pressure indicators

Degree of Fragmentation (DOF)

River fragmentation indices typically measure the degree to which river networks are fragmented longitudinally by infrastructure, such as hydropower and irrigation dams. Fragmentation prevents effective ecological processes that depend on longitudinal river connectivity, including transport of organic and inorganic matter and upstream and downstream movements of aquatic and riparian species. Because fragmentation usually obstructs the natural flow regime, it also affects lateral connectivity, including species movement and exchange of materials and energy to and from floodplains.

The Degree of Fragmentation (DOF) is a new fragmentation index at the river reach scale intended to characterize the degree and spatial extent of reduced longitudinal connectivity in the river system. It identifies river reaches up- and downstream of a dam or impoundment as being fragmented, and it assigns levels of fragmentation based on “distance” from the impact location which we determine by measuring the dissimilarity of river sizes in terms of flow quantities.

We suggest that: (1) river discharge can serve as a coarse proxy for the occurrence of species assemblages that utilize a certain range of river flow (*47*); (2) that discharge can also serve as a proxy for ‘distance’ in the traditional (spatial) sense (i.e., the further away from a given location, the more difference in discharge is expected), and increasing distance allows for amelioration effects of the fragmentation impact (e.g., through continued water and sediment influx from new tributaries and local contributing areas); and (3) that discharge changes can serve as proxies of environmental disparity and natural discontinuities because river stretches with highly dissimilar discharges, such as the confluence of a small tributary into a major river, are assumed to be less representative of continuous environmental conditions. We thus based the conceptual approach of calculating DOF on the similarity of river sizes determined by their discharges. The DOF assumes that the fragmentation effect diminishes as river sizes become increasingly dissimilar from the river size at the barrier location in both upstream and downstream directions (Fig. S3).

Guided by the involved expert group and the explicit examination of case studies from the Tapajos, Luangwa, and Ganges Rivers, we tested several different options (Fig. S4), and finally applied a 10-fold (i.e., one order of magnitude) increase or decrease in discharge as the maximum discharge range in which impacts of DOF would appear (*dr = 10; see below*). A logarithmic decay function was used to calculate the DOF values, which leads to a faster decline than a linear function. DOF has been scaled to values between 0 and 100 and is calculated in up- and downstream direction as:

$$DOF_j = 100 - \frac{\left|\log_{10} d_{bloc} - \log_{10} d_j\right| * 100}{\log_{10} dr} \tag{1}$$

where DOF_j is the DOF at river reach *j;* d_j is the natural average annual discharge of river reach *j;* d_{bloc} is the natural average annual discharge at the location of the barrier; and *dr* is the maximum discharge range.

For the DOF analysis we included 6,850 large dams as compiled in the Global Reservoir and Dam (GRanD) database (*2*) after removing a small number of dams with undefined status. We also added 13,196 medium to smaller dams from the GlObal geOreferenced Database of Dams (GOOD^2) compiled at King's College London (*48*).

The natural fragmentation effect of waterfalls has also been taken into account by incorporating a global database of 4,054 waterfalls (*49*). After removing records that were flagged as uncertain, 2,435 waterfalls were geo-located to our river reaches. The underlying premise is that waterfalls act as natural discontinuities, hence the fragmentation effect of artificial dams should not extend beyond the already existing barrier; e.g., a dam just downstream of a waterfall should not be considered to affect the river upstream of the fall. Since the barrier effect from waterfalls accounts primarily in the upstream direction, the DOF algorithm was modified to stop extending upstream if encountering the location of a waterfall, while no waterfall effect is assumed in downstream direction.

Degree of Regulation (DOR)

The Degree of Regulation (DOR) provides an index to measure how strongly a dam or set of dams can affect the natural flow regime of downstream river reaches (*2, 50*). The concept of the index is based on the relationship between the storage volume of a reservoir and the total annual river flow volume at the dam's location, and is expressed as the percentage of that flow volume that can be withheld in the dam's reservoir, represented by:

$$DOR_j = 100 * \frac{\sum_{i=1}^{n} svol_i}{d_{vol}} \tag{2}$$

where DOR_j is the DOR at river reach *j;* $svol_i$ is the storage volume of reservoirs *i* upstream of river reach *j; n* is the total number of reservoirs upstream of river reach *j;* and d_{vol} is the natural average discharge volume accumulated over a year at river reach *j.* The underlying assumption is that a large reservoir on a river with low annual discharge will generally have a larger regulatory effect on the natural flow regime than a small reservoir on a river with higher flow rates. In this study, we capped the DOR at 100%, which limits all multi-year reservoirs to the same maximum DOR. We also set DOR values below 0.1% to 0% to avoid inclusion of rivers with minimal impacts (mostly large downstream rivers affected by small and far-away headwater dams).

Consumptive water use (USE)

Water consumption for irrigation, industry, municipal uses and water transfer to other river systems may affect lateral as well as longitudinal connectivity and has implications for groundwater recharge and evaporation (vertical connectivity). Using downscaled outputs from the WaterGAP model (for details see section on 'Hydrographic framework' above), we extracted water consumptive loss for our high-resolution river network. The results provide river reach-level data on the long-term average reduction of river discharge due to anthropogenic water consumption as a percentage of natural flow:

$$USE_j = 100 * \frac{d_{nat} - d_{ant}}{d_{nat}} \qquad (3)$$

where USE_j is the consumptive water use at river reach j; d_{nat} represents the natural average annual discharge without human influences, and d_{ant} represents the average annual discharge with human abstractions and use.

Road density (RDD)

Road density is a proxy for lateral disconnection of floodplains and longitudinal loss of connectivity at intersections with streams, in particular culverts. We used the dataset produced by the "Global Road Inventory Project" (GRIP; *51*). The classified road categories 'Freeways', 'Primary', 'Secondary', and 'Tertiary' were treated equally important in our density calculations, while the category 'local, residential and urban roads' was excluded to avoid collinearity effects with the urban areas (see "Nightlight intensity in urban areas (URB)" below). We summarized the road density within a 1 km buffer around each river reach to produce an estimate of average road density (in percent of surface area covered, assuming an average road width of 50 meters) per river reach.

To eliminate isolated outlier effects on short river reaches (which in some instances can show disproportionally high road density values due to geometric artifacts rather than real situations), we applied a customized geospatial filter for all river reaches <3 km in length: we compared every river reach value with its direct upstream and downstream neighboring river reach; if the center river reach showed a value that was significantly (>15%) different from the (length-weighted) average of the two neighboring values, the center value was replaced with that average. We applied these adjustments to the road density and nightlight intensity layers (see "Nightlight intensity in urban areas (URB)" below), resulting in corrections of 0.0003% and 0.006% of affected river reaches, respectively.

Nightlight intensity in urban areas (URB)

Urban areas and cities affect lateral connectivity by confining the river bed and affecting river meandering (*52*). Several studies on urbanization and rivers show consistently that about 10% of contiguous impervious area within a catchment typically causes an observable and probably irreversible river degradation and loss of ecosystem functions (*53-55*). As a proxy for channelization of rivers and alterations of floodplains due to paving and urban infrastructure, we used the global dataset of nightlight intensity data from Doll (*56*; DMSP-OLS v4) and accounted for the "light-bleeding" effect into adjacent areas (*57*) by clipping the nightlights dataset using the MODIS-based urban extent layer by Schneider *et al.* (*58*). We summarized the data within the contributing sub-catchment of each river reach to produce an average night light intensity for each river reach and applied the outlier correction as described in "Road density (RDD)" above.

Determination of Connectivity Status Index (CSI)

The five individual pressure indicators were scaled to the range of 0-100 prior to the calculation of CSI. The conceptual approach to calculate the CSI for an individual river reach is then to produce a weighted average of the five pressure indicators, and to subtract it from the maximum of 100%, as described by the equation:

$$CSI_j = 100 - \frac{\sum_{i=1}^{n} x_i * w_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

where CSI_j is the Connectivity Status Index at river reach j; x_i is the value of pressure indicator i; w_i is the weight applied to the pressure indicator i; and n is the number of pressure indicators (in our case 5). The resulting CSI represents values from 0% (not connected) to 100% (fully connected).

For the pressure indicators RDD and URB, we modified the weighting factors by multiplying the weights with a factor that is proportional to the extent of floodplains around the river, assuming that roads and urban development within floodplains are particularly likely to affect latitudinal connectivity. We used the long-term maximum inundation extent as provided in the global inundation map GIEMS-D15 (*59*) and allowed a maximum increase of the weight by a factor of 1.5 if all roads or urban areas were inside floodplains:

$$x_i = \tilde{x}_i * (1 + \frac{f_j}{2}) \tag{5}$$

where x_i is the value of the pressure indicator i (RDD or URB) after floodplain weighting; $\tilde{x}_i$ is the value of the pressure indicator i (RDD or URB) without floodplain weighting; and f_j is the fraction of floodplain extent within the contributing sub-catchment of river reach j.

This approach of calculating CSI poses the challenge of finding appropriate weights for each pressure indicator. To achieve this, we followed a two-part approach: first, we defined plausible ranges of weights based on a literature review and expert judgement (see "Plausible weighting ranges" below). We then created 10 scenarios where we manipulated the individual weights within the plausible ranges and compared the results of each scenario to a set of benchmark rivers reported to be free-flowing (see "Benchmarking and sensitivity analysis" below). For the final CSI application, we selected the weights of the scenario that best reproduced the FFR status of the benchmark rivers (scenario 5).

Plausible weighting ranges

The definition of plausible weighting ranges was the result of a process that combined (1) expert knowledge and judgement and (2) known responses of river systems based on literature (see Table S3). As there is no direct quantification available in literature to describe the relative importance of our five individual pressure indicators, we used an indirect method of setting the weighting ranges: We first chose a combined CSI threshold beyond which an individual river reach should no longer be considered to have a 'good connectivity status'—after several iterations in the benchmarking exercise this threshold was set to be 95%. We then identified limits for each individual pressure indicator beyond which it should cause a river reach to fall below this CSI threshold and be declared impacted; we termed this limit the 'Single Pressure

Limit' (SPL). For example, a road density of 5–30% has been linked to negative effects on aquatic ecosystems due to fragmentation issues (Table S3) and can thus serve as the SPL range. Once both the CSI threshold and a plausible SPL range are known, Eq. 4 can be transformed to calculate the minimum weight w_{min} that is required to assure that a given SPL will cause a river reach to fall below the CSI threshold:

$$w_{min} = \frac{100 - CSI\ threshold}{SPL} \tag{6}$$

For example, a minimum weighting of 20% will cause the CSI value to fall below the threshold of 95% for all river reaches with an RDD indicator of 25% or higher (i.e., a value in the plausible SPL range). Using this method, we defined plausible weighting ranges that reflect the SPL ranges we found in literature (Table S3).

Benchmarking and sensitivity analysis

The purpose of benchmarking was to fine-tune the pressure indicator weights as well as the CSI threshold so that rivers which are well-known for their unaffected connectivity (as determined by expert opinion or existing assessments) achieve free-flowing status in our results. For this purpose we created a reference database of reported FFRs using sources from Nilsson *et al.* (*24*), and from expert knowledge. The reported 159 rivers were distributed across the world, and ranged between 20 km and 3,300 km in length (for a complete list see 'External Database S2').

To compare different weight settings, as well as to test the sensitivity of the results to those settings, we explored ten different weighting scenarios (see Table S4). We assigned varying weights to the individual pressure indicators representing different SPL ranges and produced statistics and maps for visual inspection. To determine the level of agreement between scenario results and benchmarking rivers, we calculated the percentage of rivers which we correctly classified as free-flowing.

In general, the benchmarking analysis showed high levels of agreement of the free-flowing status of rivers between its results and the reference rivers (Table S5). The range of agreement among scenarios was relatively narrow, between 87.4% and 93.1%, making selection of a clearly optimal scenario difficult. We ultimately selected scenario 5, which had the highest correct classification rate for the reference rivers.

Scenario 5 set the SPL value of the Degree of Fragmentation (DOF) at 40% (weighting of 10.3%); i.e., any river reaches with a DOF value larger than 40% will be determined as impacted (Table S6). The relatively high SPL value corresponds with a low weight for this indicator, which reflects a conservative approach given the novelty of the DOF approach and the lack of comparable studies that measure fragmentation in a similar way. Nevertheless, due to the high number of dams and their wide-ranging fragmentation effects, approximately 246,000 river reaches were declared impacted (CSI <95%) due to DOF alone, representing 86% of all 285,000 impacted river reaches.

The SPL value of the Degree of Regulation (DOR) was set at 15% (weighting at 27.6%), which is on the high end of the plausible SPL range for this indicator, again representing a cautious approach. Other studies have determined effects from river regulation as low as 2% (*50*). Nevertheless, almost 133,000 river reaches (46% of impacted river reaches) are impacted due to DOR alone, making flow regulation the second most common pressure factor.

Consumptive water use (USE) is known to have a direct effect on river functions according to our literature review. The SPL value for USE in scenario 5 was set at 10% (weighting at

41.4%), which is below the often-cited threshold of 20% for consumptive water use as an indicator of ‘severe’ water stress (*60-62*). Nevertheless, given that water consumption is an important factor only in relatively dry areas of the world, and that only about 20% of the river reaches affected by water consumption showed a value larger than 10%, the overall importance of this factor is relatively low, with roughly 133,000 river reaches (46% of impacted river reaches) being impacted due to USE alone.

The RDD pressure indicator received a relatively high SPL value of 30% (weighting of 13.8%), which agrees with a lower level of confidence regarding the effect of roads near a river on its FFR status. With this SPL threshold, only river reaches with road densities above 30% (after floodplain adjustment) are declared as being impacted. Even though roads are widespread and penetrate even remote areas, we identified only 194 reaches (<0.1% of impacted river reaches) where RDD alone was causing a river reach to become not free-flowing.

Given the similarly low confidence of accurately representing the effect of nightlight intensity in urban areas on connectivity, we set the URB indicator to a high SPL value of 60% (weighting of 6.9%). Areas with increased nightlight intensity are much more extensive than areas with high road density, so URB alone marked almost 21,000 river reaches as impacted, representing 7% of all impacted river reaches.

As in the final CSI calculations the individual pressure indicators can overlap or complement each other to reduce the CSI below the 95% threshold, the total number of impacted river reaches is not the sum of the individual values stated above, but all factors together impact a total of 285,000 river reaches. Given the cautious selection of CSI threshold and weights, we believe that overall our conservative settings tend more towards under- than overestimations of the extent of impacted river reaches.

Identification of free-flowing rivers

Using the backbone concept as described in the ‘Hydrographic framework’ section above, and considering a CSI threshold of 95%, we classified the river network into (Fig. S5):

1) ‘Free-flowing rivers’: Rivers that are above the CSI threshold from their source to the river outlet.
2) ‘Good connectivity status’: A river reach or a stretch of river above the CSI threshold, but other river reaches or stretches of the same river are below the CSI threshold.
3) ‘Impacted’: Any river reach, stretch, or entire river that is below the CSI threshold.

In some cases, a major river may have a few river reaches or short stretches below the CSI threshold, e.g., due to a small fragmentation in a remote headwater location, which according to our definitions would render the entire river as not free-flowing. To limit these minor artifacts, we excluded impacts of small reaches or stretches that affect less than 0.1% of the total flow of the river (in terms of average natural discharge). Globally, this filter only affects 316 river reaches or stretches with a total length of 1,709 km.

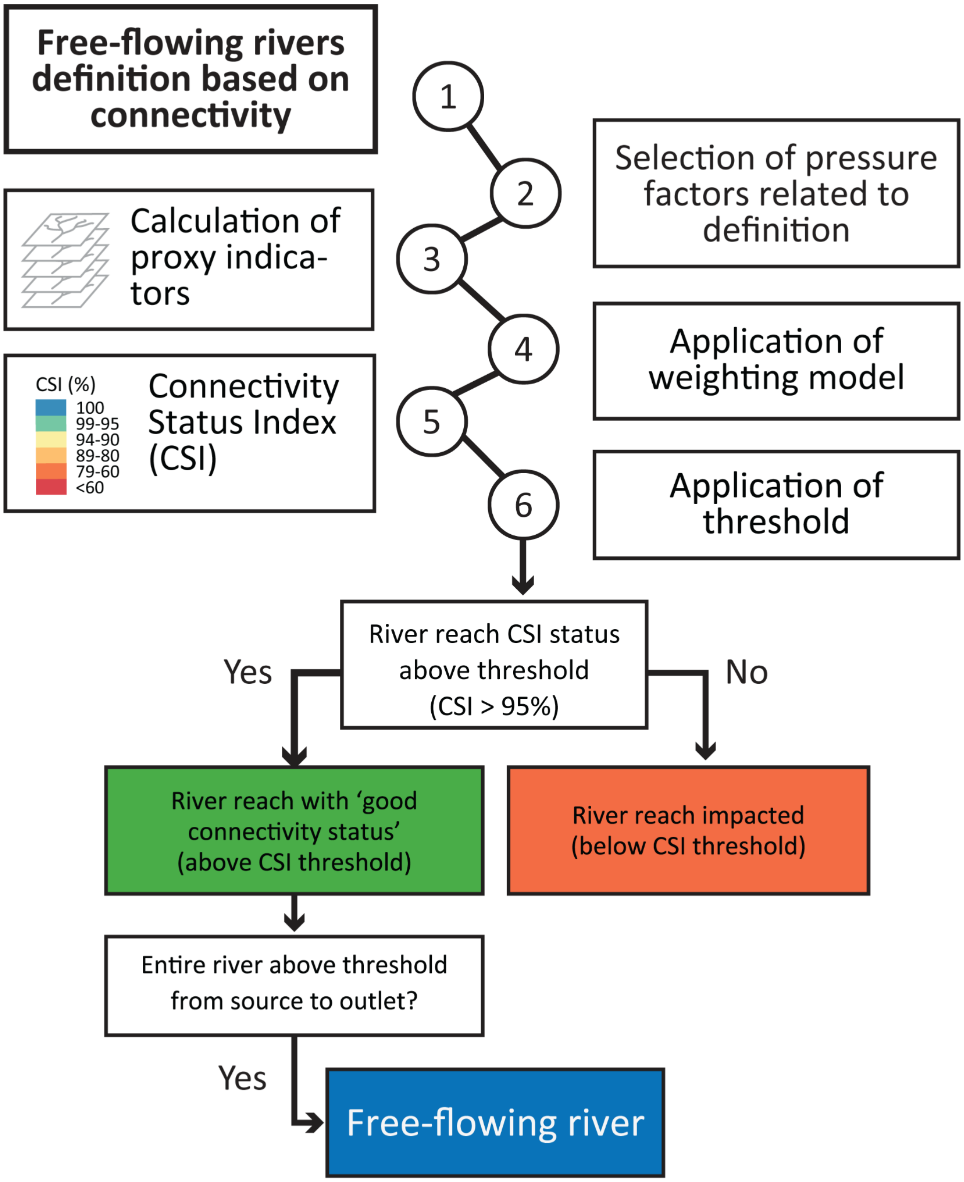
Supplementary Text

Definition of free-flowing rivers

Over the course of 2.5 years, a group of over 30 scientists, conservation practitioners, and industry representatives collaboratively contributed to updating an earlier global assessment of free-flowing rivers (*63*). We identified several definitions and methodologies for free-flowing rivers from a literature review and summarized key indicators and datasets used. The following definition of a free-flowing river was agreed upon to comprehensively include all components of fluvial connectivity:

> "A free-flowing river is a river where natural aquatic ecosystem functions and services are largely unaffected by changes to the fluvial connectivity allowing an unobstructed exchange of material, species and energy within the river system and surrounding landscapes. Fluvial connectivity encompasses longitudinal (river channel), lateral (floodplains), vertical (groundwater and atmosphere) and temporal (intermittency) components and can be compromised by (a) physical infrastructure in the river channel, along riparian zones, or in adjacent floodplains; (b) by hydrological alterations of river flow due to water abstractions or regulation; and (c) by changes to water quality that lead to ecological barrier effects caused by pollution or alterations in water temperature."

764 **Supplementary Figures and Tables**



765

766 **Fig. S1:** Workflow to map free-flowing rivers.

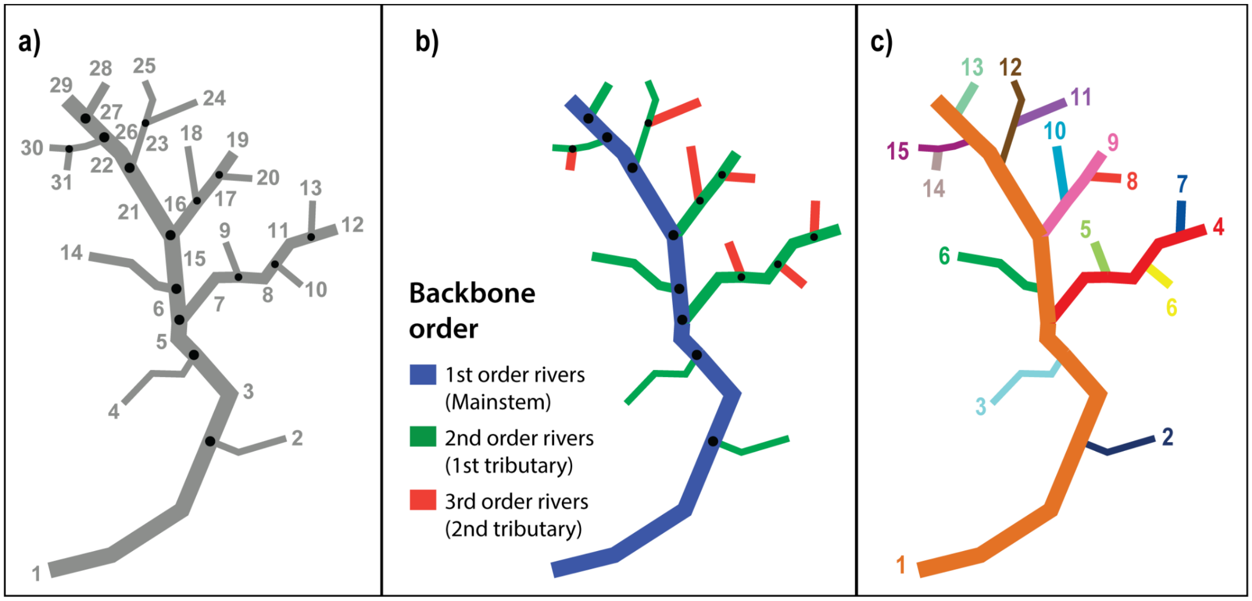


Fig. S2: Schematic overview of river-related concepts used in this study. The baseline river network consists of individual river reaches (1-31 in panel a), defined as line segments separated by confluences (black dots). River reaches can be aggregated into rivers based on a 'backbone' ordering system which classifies river reaches as the mainstem or a tributary of various higher orders (b). Following this system, the river network can be distinguished into distinct rivers (1-15 in panel c), defined as a contiguous stretch of river reaches from source to outlet on the mainstem, or from source to confluence with the next order river.

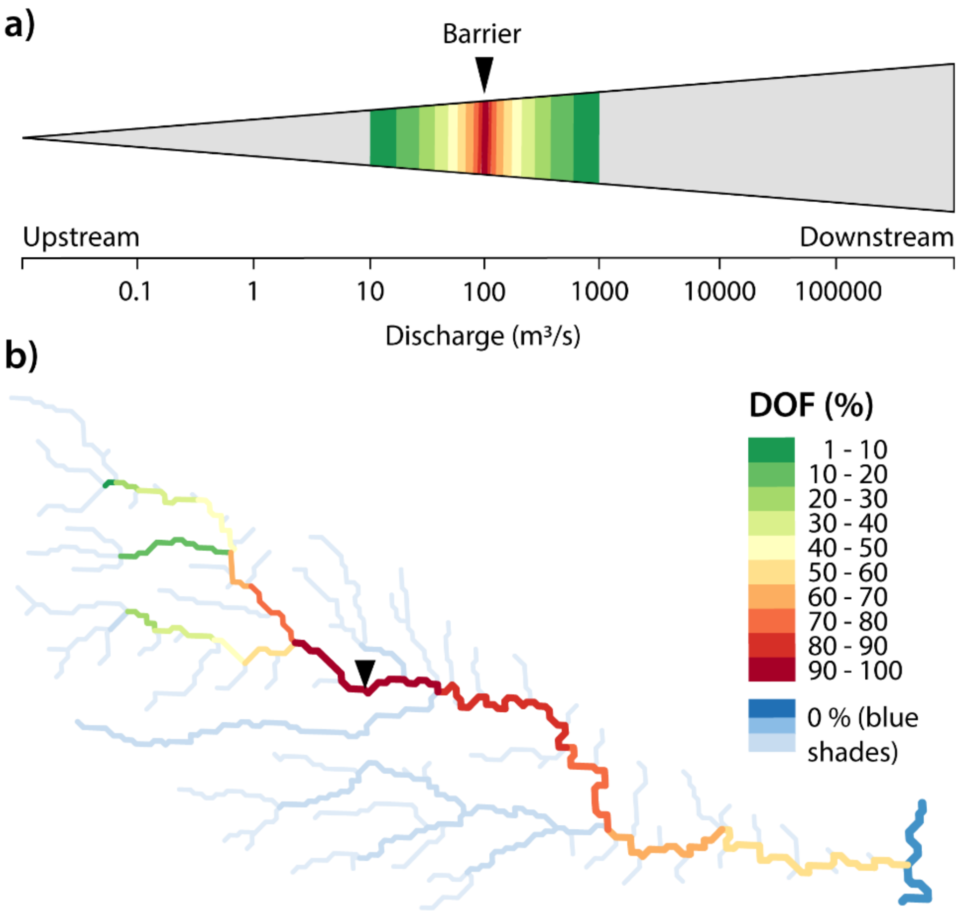


Fig. S3: Conceptual approach of the DOF calculation (a) and visualization for a river example (b). The DOF index ranges from 0% (no fragmentation impact) to 100% (completely fragmented) as shown in the legend (b). It is calculated for all river reaches connected to the barrier location in the upstream and downstream direction (yet tributaries to the mainstem downstream of the barrier are not considered affected). The impact is largest in connected river reaches that are similar in discharge to the barrier site, and diminishes as rivers become increasingly dissimilar in size, i.e., larger in the downstream or smaller in the upstream direction.

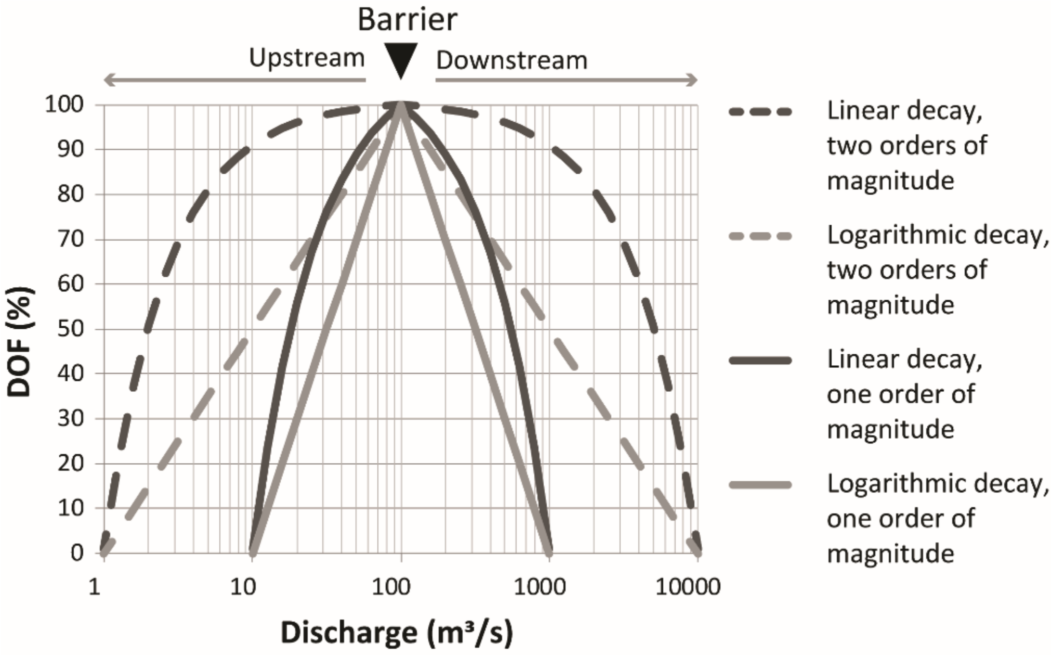


Fig. S4: DOF decay functions as considered and evaluated by expert group.

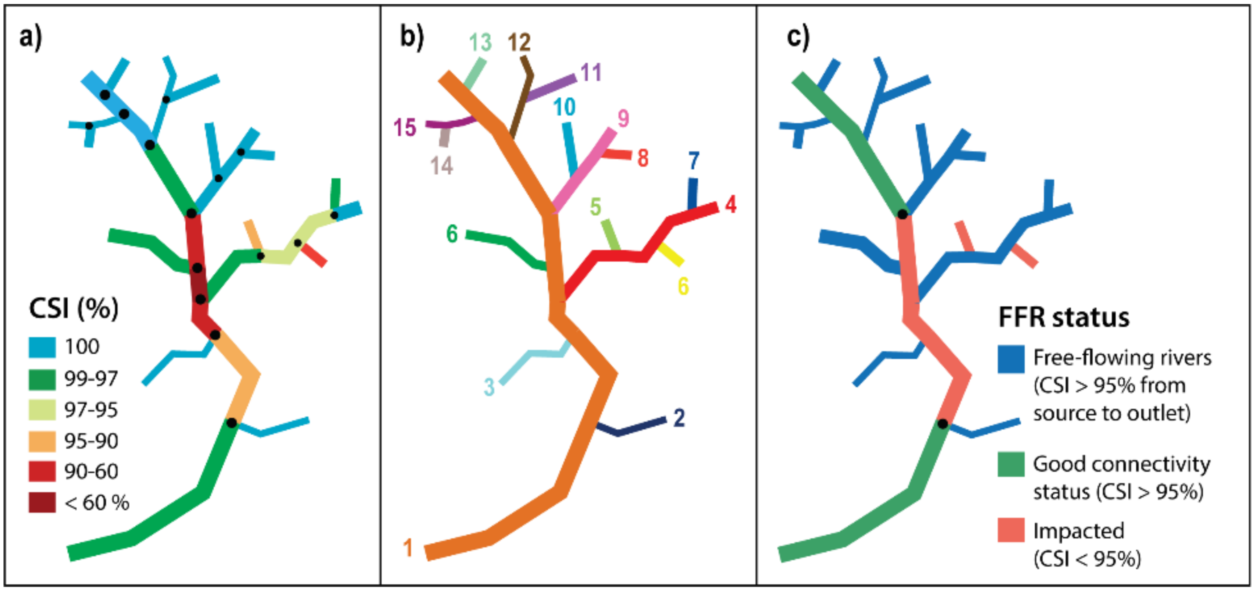


Fig. S5: CSI values for each individual river reach as calculated with our model (a). If a value is above the CSI threshold (95%), the river reach is declared to have a 'good connectivity status'; if it is below the threshold, it is declared to be impacted. If an entire river (as defined in Fig. S2c, replicated here in panel b) has 'good connectivity status', it is defined to be a free-flowing river (blue rivers in panel c). A river can partly be above the CSI threshold, and thus contiguous stretches can have 'good connectivity status', shown in green.

Table S1: Number (a) and length (b) of river stretches in ‘good connectivity status’ (CSI ≥ 95%) by river length class and continent.

a)	**‘Good Connectivity Status’ (number of rivers)**				
	10–100 km	**100–500 km**	**500–1000 km**	**>1000 km**	**Total**
Africa	417	181	13	3	**614**
Asia	2,802	370	21	8	**3,201**
Australia	355	68	7		**430**
Europe	2,058	316	12		**2,386**
North America	1,637	236	1	1	**1,875**
South America	996	213	11	7	**1,227**
Total	**8,265**	**1,384**	**65**	**19**	**9,733**

b)	**‘Good Connectivity Status’ (thousand km)**				
	10–100 km	**100–500 km**	**500–1000 km**	**>1000 km**	**Total**
Africa	17.5	40.5	8.8	3.8	**70.6**
Asia	88.2	69.2	14.0	15.5	**187.0**
Australia	11.4	13.1	4.2		**28.6**
Europe	78.7	54.2	7.4		**140.4**
North America	58.8	39.3	0.6	1.0	**99.7**
South America	35.6	41.0	7.1	12.1	**95.8**
Total	**290.2**	**257.4**	**42.0**	**32.5**	**622.2**

Table S2: Pressure indicators used in this study and their data sources

Indicator	**Description**	**Connectivity aspect affected**	**Source data**
DOF	Degree of Fragmentation	Longitudinal	HydroSHEDS; Lehner *et al.* (*26*); GRanD v1.1; Lehner *et al.* (*2*); GOOD2 v1; Mulligan *et al.* (*48*)
DOR	Degree of Regulation	Longitudinal, lateral, vertical, temporal	HydroSHEDS; Lehner *et al.* (*26*); GRanD v1.1; Lehner *et al.* (*2*); GOOD2 v1; Mulligan *et al.* (*48*); HydroLAKES, v1.0; Messager *et al.* (*64*)
RDD	Road density	Lateral	GRIP v3; Meijer and Klein Goldewijk (*51*)
URB	Nightlight intensity in urban areas	Lateral	DMSP-OLS v4; Doll (*56*); Modis-derived urban areas Schneider *et al.* (*58*)
USE	Consumptive water use (abstracted from rivers)	Longitudinal, lateral, vertical, temporal	WaterGAP v2.2 as of 2014; Alcamo *et al.* (*45*), Döll *et al.* (*46*)

Table S3: Overview of literature used for determining plausible 'Single Pressure Limit' (SPL) ranges.

Pressure indicator	**Range of SPL values reported**	**Relevant literature and case studies**
DOF	10-50	Pracheil *et al.* (*47*); Expert review; Case studies in Tapajos, Luangwa and Upper Ganges River
DOR	2-15	Lehner *et al.* (*2*), Nilsson and Berggren (*9*), Richter *et al.* (*65*), Nilsson and Jansson (*66*)
USE	10-40	Falkenmark *et al.* (*60*), Smakhtin *et al.* (*61*), Alcamo *et al.* (*62*), Brauman *et al.* (*67*)
RDD	5-30	Blanton and Marcus (*68*), Shuster *et al.* (*69*)
URB	> 80 (for representing urban effects; scaled)	Booth and Jackson (*54*), Blanton and Marcus (*68*), Shuster *et al.* (*69*), Schueler *et al.* (*70*)

Table S4: Weights and 'Single Pressure Limit' (SPL) of the applied set of 10 scenarios.

	Pressure indicator				
Scenario	**DOF**	**DOR**	**NLI**	**RDD**	**CON**
1					
SPL (5%)	50.0	15.0	70.0	50.0	25.0
Weights (%)	12.4	41.4	8.9	12.4	24.9
2					
SPL (5%)	40.0	25.0	70.0	50.0	30.0
Weights (%)	18.9	30.2	10.8	15.1	25.1
3					
SPL (5%)	40.0	10.0	70.0	50.0	30.0
Weights (%)	13.0	51.9	7.4	10.4	17.3
4					
SPL (5%)	50.0	15.0	80.0	40.0	20.0
Weights (%)	11.5	38.3	7.2	14.4	28.7
5					
SPL (5%)	40.0	15.0	60.0	30.0	10.0
Weights (%)	10.3	27.6	6.9	13.8	41.4
6					
SPL (5%)	30.0	10.0	70.0	30.0	40.0
Weights (%)	16.2	48.6	6.9	16.2	12.1
7					
SPL (5%)	20.0	10.0	60.0	40.0	30.0
Weights (%)	22.2	44.4	7.4	11.1	14.8
8					
SPL (5%)	25.0	15.0	50.0	50.0	25.0
Weights (%)	21.4	35.7	10.7	10.7	21.4
9					
SPL (5%)	50.0	15.0	90.0	50.0	30.0
Weights (%)	13.2	44.1	7.4	13.2	22.1
10					
SPL (5%)	70.0	25.0	70.0	70.0	15.0
Weights (%)	9.6	26.8	9.6	9.6	44.6
Min	**9.6**	**26.8**	**6.9**	**9.6**	**12.1**
Average	**14.9**	**38.9**	**8.3**	**12.7**	**25.2**
Max	**22.2**	**51.9**	**10.8**	**16.2**	**44.6**
Range	**12.7**	**25.2**	**3.9**	**6.6**	**32.4**

Table S5: Results of the benchmarking by category showing rivers that were nominated by experts during workshop, as well as rivers from Nilsson et al. (2005).

Scenario	**S01**	**S02**	**S03**	**S04**	**S05**	**S06**	**S07**	**S08**	**S09**	**S10**
	Expert nominated									
Mismatch	7	10	6	7	5	6	8	10	7	5
Match	32	29	33	32	34	33	31	29	32	34
Correct classification %	**82.1**	**74.4**	**84.6**	**82.1**	**87.2**	**84.6**	**79.5**	**74.4**	**82.1**	**87.2**
	Nilsson *et al.* (2005)									
Mismatch	8	10	7	7	6	8	8	9	7	7
Match	112	110	113	113	114	112	112	111	113	113
Correct classification %	**93.3**	**91.7**	**94.2**	**94.2**	**95.0**	**93.3**	**93.3**	**92.5**	**94.2**	**94.2**
Total benchmark rivers	159	159	159	159	159	159	159	159	159	159
Overall correct classification %	**90.6**	**87.4**	**91.8**	**91.2**	**93.1**	**91.2**	**89.9**	**88.1**	**91.2**	**92.5**

Table S6: Selected weighting scenario (scenario 5) based on benchmarking results, its 'Single Pressure Limit' (SPL), as well as corresponding weighting values.

Pressure indicator	**DOF**	**DOR**	**USE**	**RDD**	**URB**	**Sum**
SPE (95%)	40.0	15.0	10.0	30.0	60.0	n.a.
Weights (%)	10.3	27.6	41.4	13.8	6.9	100
Number of river reaches predominantly affected by pressure indicator[1]	138,630	96,790	42,103	308	7,243	285,074
Number of river reaches affected by pressure indicator alone[2]	246,355	133,120	132,791	194	20,678	n.a.

[1] This row summarizes the number of times a pressure indicator had the highest weight on the CSI index taking into account multiple pressure indicators.

[2] This row indicates how many times a pressure indicator decreases the CSI below the threshold by itself.

Additional Data table S1 (separate EXCEL file: DB_S1_Major_FFRs.xls)

List of free-flowing rivers longer than 500 km by continent.

Additional Data table S2 (separate EXCEL file: DB_S2_Ref_Rivers.xls)

List of reference rivers evaluated for benchmarking. Sources: ‘Expert nominated’ (BENCH_SCR = ‘EXP’) and Nilsson *et al.* (*24*) (BENCH_SCR = ‘NLS’).