Fragmentation and Flow Regulation of the World's Large River Systems

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A global overview of dam-based impacts on large river systems shows that over half (172 out of 292) are affected by dams, including the eight most biogeographically diverse. Dam-impacted catchments experience higher irrigation pressure and about 25 times more economic activity per unit of water than do unaffected catchments. In view of projected changes in climate and water resource use, these findings can be used to identify ecological risks associated with further impacts on large river systems.

Humans have extensively altered river systems through impoundments and diversions to meet their water, energy, and transportation needs. Today, there are >45,000 dams above 15 m high, capable of holding back >6500 km^3 of water (*1*), or about 15% of the total annual river runoff globally (*2*). Over 300 dams are defined as giant dams, which meet one of three criteria on height (>150 m), dam volume (>15 million m^3), or reservoir storage (>25 km^3) (*3*). The recently constructed Three Gorges Dam on the Chang Jiang (Yangtze) in China is the largest, 181 m high and with a reservoir storing >39 km^3 (*4*, *5*). Although statistics summarizing the world's large dams are available (*3*, *4*, *6*, *7*), detailed multiscale data have not been synthesized globally.

Catchment-scale impacts of dams on ecosystems are generally well known, with both upstream and downstream effects stemming from inundation, flow manipulation, and fragmentation (*8–10*). Inundation destroys terrestrial ecosystems and eliminates turbulent reaches, disfavoring lotic biota. It can cause anoxia, greenhouse gas emission, sedimentation, and an upsurge of nutrient release in new reservoirs (*6*, *11*, *12*). Resettlement associated with inundation can result in adverse human health effects and substantial changes in land use patterns (*13*, *14*). Flow manipulations hinder channel development, drain floodplain wetlands, reduce floodplain productivity, decrease dynamism of deltas, and may cause extensive modification of aquatic communities (*15–18*). Dams obstruct the dispersal and migration of organisms, and these and other effects have been directly linked to loss of populations and entire species of freshwater fish (*19–21*). The World Commission on Dams produced the most comprehensive review of dam impacts yet (*22*), with illustrative catchment-scale case studies. However, data were not available for a global analysis based on subcatchment-scale resolution, integrating hydrologic, ecological, and socioeconomic data. Such a synthesis is needed to understand the multiple spatial, temporal, and interactive impacts of dams.

Here, we present a global overview of flow regulation and channel fragmentation in the world's largest river systems, which comprise a total virgin mean annual discharge (VMAD, the discharge before any substantial human manipulations) of some 790,000 m^3 s^{-1}, or 60% of the world's river runoff. We proceeded by (i) identifying 153 large river systems (LRSs) in Latin America, Africa, Asia, and Australasia that we had not previously assessed (*23*), (ii) locating and gathering storage capacity data for their dams, (iii) quantifying channel fragmentation by dams, (iv) and quantifying flow regulation by relating storage capacity to discharge. We also updated these same data for 139 systems that we had previously assessed in the Northern Hemisphere (*23*), combined the two data sets for a total of 292 river systems, and, on the basis of these data, classified the river systems as either unaffected, moderately affected, or strongly affected (*24*). We were unable to assess rivers in most of Indonesia and a small part of Malaysia (because of a lack of reliable discharge data). We included irrigation data for all 292 LRSs and analyzed global distribution of impact relative to terrestrial biomes and economic activity.

We defined an LRS as a system that has, anywhere in its catchment, a river channel section with a VMAD of ≥350 m^3 s^{-1} (*23*, *25*). By river system, we mean entire networks of stream and river channels interconnected by surface freshwater, from the headwaters to the sea (*26*). The 292 LRSs (table S1 and Fig. 1) drain 54% of the world's land area. North and Central America contain more LRSs (88 total) than any other continent, but on average these systems contribute less water and have smaller catchment areas than do those of Asia, Africa, and South America. Of the 10 LRSs with highest discharge, 6 lie in Asia, 2 in South America, 1 in Africa, and 1 in North and Central America.

The catchments of LRSs encompass at least some part of all 16 of the world's nonmarine biomes as classified by Olson *et al*. (*27*) and >50% of 11 of these biomes, including 87% of all boreal forests and 83% of all flooded grasslands and savannahs. The biomes with least proportion of their surface area in LRSs are rock and ice (1%); mangroves (17%); and Mediterranean forests, woodlands, and scrub (19%). In all, 72 LRSs span only one biome, whereas the Ganges-Brahmaputra system (AS-65) encompasses the widest diversity (10 biomes), followed by the Amazonas-Orinoco (SA-11; these rivers have a natural cross-channel), Amur (AS-20), Yenisei (AS-5), Zambezi (AF-6), and Indus (AS-73) systems, each spanning eight.

Nearly half (139) of all LRSs (48%) remain unfragmented (*28*) by dams in the main channel, 119 systems (41%) have unfragmented tributaries, and 102 systems (35%) are completely unfragmented. Europe contains the smallest number of completely unfragmented LRSs (just three rivers in northwestern Russia). The continent with the greatest number (35) of unfragmented LRSs is North and Central America, and the greatest proportion is in Australasia (74%). Twelve LRSs (9 in Europe and 3 in the United States) have <25% of the main channel's length left unfragmented.

The greatest flow regulation (*29*) was for the Volta river system in Africa (AF-19, 428%). In North and Central America, both the Manicougan (NA-35) and Colorado (NA-70) systems are regulated >250%, and in South America the most highly regulated system is the Rio Negro in Argentina (SA-22, 140%). The most highly regulated systems in Asia are the Shatt Al Arab (or Euphrates-Tigris) in the Middle East (AS-74, 124%) and the Mae Khlong in Thailand (AS-58, 130%). Flow regulation does not exceed 100% in any LRS in Europe or Australasia. A flow regulation of 100% indicates that the entire discharge of one year could be held back and released by the dams in the river system.

The numbers of unaffected and strongly affected LRSs are roughly equal (120 and 104, respectively), whereas moderately affected systems represent just 23%, or 68 of the 292 LRSs (Fig. 1). Of the 10 LRSs with highest discharge, 6 are moderately affected and 4 are strongly affected. The world's two largest discharges, the Amazonas-Orinoco and Congo, are moderately affected, and the third largest discharge, the Chang Jiang, is strongly affected (table S1). The largest unaffected LRS is the

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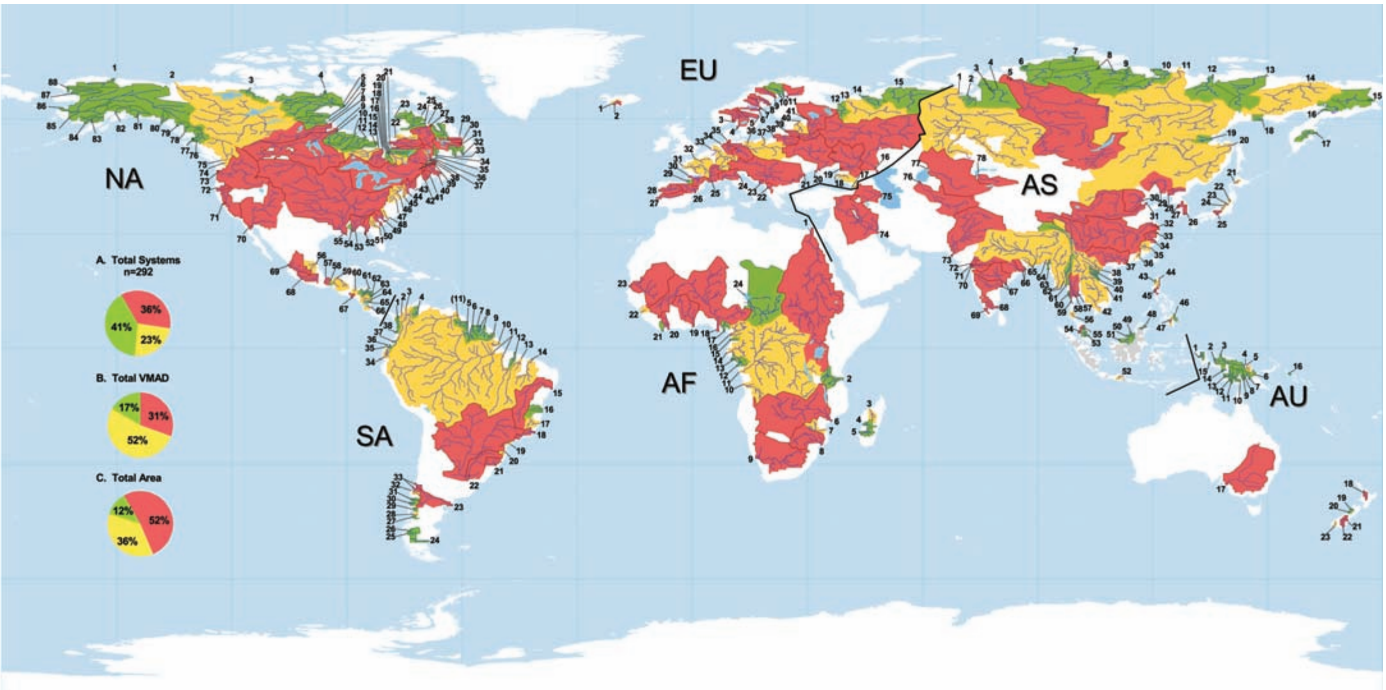

Fig. 1. Impact classification based on river channel fragmentation and water flow regulation by dams on 292 of the world's large river systems. River systems are treated as units and are represented on the map by their catchments. Numbers refer to the list of LRSs in table S1. Green, yellow, and red indicate unimpacted, moderately impacted, and strongly impacted catchments, respectively. White areas indicate land not covered by LRSs. Systems excluded from the study for lack of data are shown in gray. Diagrams at left show A, total number of LRSs; B, total VMAD of LRSs; and C, total surface area of LRSs. NA, North and Central America; SA, South America; AF, Africa; EU, Europe; AS, Asia; AU, Australasia.

Yukon (22nd highest VMAD). Strongly affected systems constitute the majority (52% or 41.2×10^6 km^2) (Fig. 1) of total LRS catchment area, despite contributing less water per system (2326 m^3 s^{-1}) and per system catchment area (396×10^3 km^2) than moderately affected LRSs. Among continents, the highest number (40) of unaffected LRSs is in North and Central America, whereas Australasia contains the highest proportion (74%) of unaffected systems. Europe has both the smallest number (five) and smallest proportion (12%) of unaffected LRSs (Fig. 2).

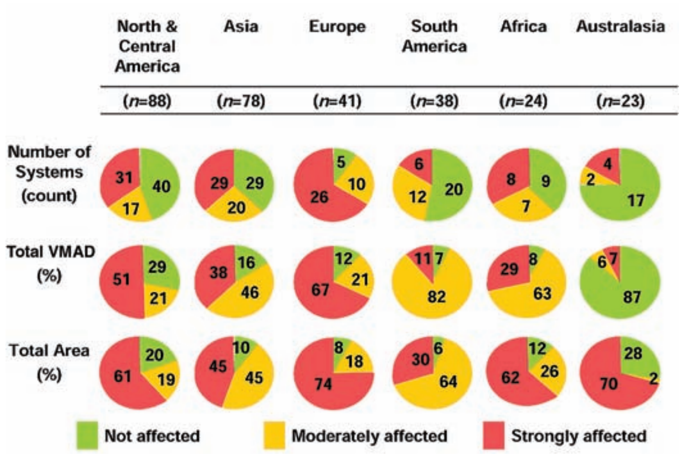

Fig. 2. Total number of systems, total water discharge, and total basin area of strongly affected, moderately affected, or unaffected within each continent's LRSs. Percentages may not total 100% because of independent rounding.

Fourteen unaffected or moderately affected LRSs nearly meet fragmentation and regulation criteria for higher impact classification (NA-14, 47, 48, 54, and 80; SA-28 and 32; EU-18, 29, and 33; and AS-1, 24, 35, and 36). Small increases in flow regulation caused by irrigation could change these classifications. Although many dams provide water for irrigation, nonreturned withdrawal from a river's flow for irrigation is a separate and additional form of flow regulation to that caused by retention and release of water by dams. To assess this, we constructed an irrigation index representing the area equipped for or under irrigation (*30*) within each LRS per unit of water in the system (table S1).

Strongly affected systems account for the 25 highest irrigation index values, 15 of which lie in Asia, with the Haihe in China (AS-30) scoring the highest (2194 km^2 per annual km^3 of discharge) (table S1). Of the five borderline unaffected systems, index values only suggest reclassification (to moderately affected) for the Adour in France (EU-29). Of the nine borderline moderately affected systems, index values were high enough to suggest reclassification (to strongly affected) for five systems: Bío-Bío in Chile (SA-32), Kuban in western Russia (EU-18), Agano-Gawa in Japan (AS-24), and Min Jiang and Han Jiang in China (AS-35 and 36, respectively).

Most of the unaffected LRSs are situated in just four biomes (tundra; boreal forests; tropical and subtropical moist broadleaf forests; and tropical and subtropical grasslands, savannahs, and shrublands) (Fig. 3), constituting small proportions of each biome. Tundra, which is sparsely populated, relatively flat, and thus unfavorable to dam construction, is the only biome in which LRS catchment area (29% of total biome area) is predominantly unaffected (73%). Even if unassessed river systems are assumed to be unaffected (a best-case scenario), the maximum proportion of unaffected biome area is still <40% for each of boreal forests; tropical and subtropical moist broadleaf forests; and tropical and subtropical grasslands, savannahs, and shrublands.

Catchment area of strongly affected LRSs constitutes >50% of three biomes (temperate

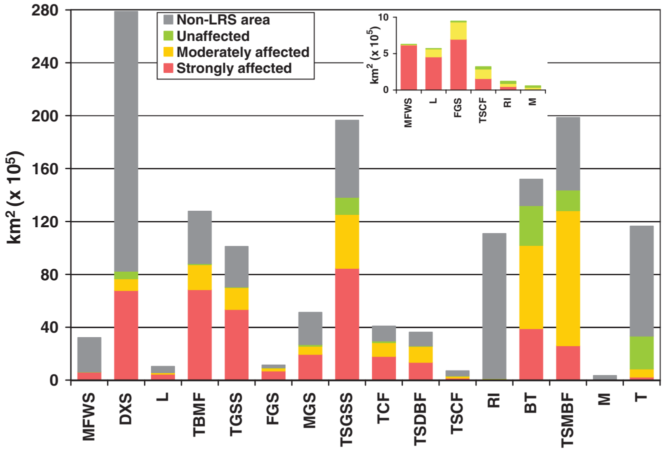

Fig. 3. Distribution of surface area within each of the world's 16 nonmarine biomes among the catchments of unaffected, moderately affected, or strongly affected LRSs; gray represents a non-LRS area, including potential LRSs in Indonesia and Malaysia. Biomes are listed in descending order from left to right by proportion of strongly affected area within LRS-covered area. **(Inset)** Increased resolution of impact class distribution for six biomes with little LRS-covered area. MFWS, Mediterranean forests, woodlands, and scrub; DXS, desert xeric shrubs; L, lakes; TBMF, temperate broadleaf mixed forests; TGSS, temperate grasslands, savannahs, and shrublands; FGS, flooded grasslands and savannahs; MGS, montane grasslands and shrublands; TSGSS, tropical and subtropical grasslands, savannahs, and shrublands; TCF, temperate conifer forests; TSDBF, tropical and subtropical dry broadleaf forests; TSCF, tropical and subtropical coniferous forests; RI, rock and ice; BT, boreal forests/taiga; TSMBF, tropical and subtropical moist broadleaf forests; M, mangroves; and T, tundra.

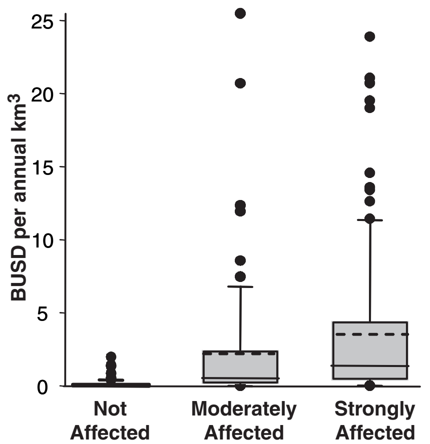

Fig. 4. Distribution of GLP [in billions U.S. dollars (BUSD)] within not affected (n = 120), moderately affected (n = 68), and strongly affected (n = 104) LRSs. Percentile divisions are 10 (not visible), 25, 50, 75, and 90; means are shown as dotted lines.

broadleaf and mixed forests; temperate grasslands, savannahs, and shrublands; and flooded grasslands and savannahs). Within the catchment area of LRSs, 82% is strongly affected in deserts and xeric shrublands, and 99% in Mediterranean forests, woodlands, and scrubs. Flow regulation, implying reduced flooding and less productive floodplains, may be especially harmful in the dry and cold biomes where species are particularly dependent on the riparian resource (*31*, *32*).

The eight LRSs that span seven or more biomes are all moderately or strongly impacted (SA-11; AS-1, 5, 20, 62, 65, and 73; and AF-6) (table S1). Of the 37 LRSs that span five or more biomes, only five remain unaffected (Catatumbo, SA-4; Salween, AS-61; Rufiji, AF-2; Mangoky AF-5; and the Chari, AF-24) (table S1). In these biogeographically diverse LRSs, the impacts of dams are more widespread than those in less diverse systems, because more ecotones are affected by fragmentation.

Moderately and strongly affected LRSs already dominate several biomes, and those biomes may become totally devoid of unaffected river systems if this pattern persists in the smaller basins and subbasins. Indeed, previous results from the Nordic countries show that the regional distribution of impact classes is similar between LRSs and small- and medium-sized river basins (*23*).

In the past century, dam construction has coincided with economic development at the national and regional scales (*22*). To examine the current state of this relationship at the basin scale, we calculated a per-discharge gross LRS product (GLP) accounting for basin population, associated national economies, and VMAD (*33*). Results show that basin impact increases with economic activity, and average GLP of unaffected LRSs is 25 times lower than that of both moderately and strongly affected LRSs (Fig. 4). There are five strongly affected LRSs with negligible GLPs [<$1 million (U.S.) km^{-3}] (table S1), all in northern Canada. These systems lie in sparsely populated regions (driving the low GLPs), and dam benefits (hydropower) are exported to other basins (*34*).

There are 46 LRSs for which large dams are planned or under construction, with anywhere from 1 to 49 new dams per basin (*35*). Forty of these LRSs are in non-OECD (Organization for Economic Cooperation and Development) member nations, indicating that future dam development does not depend on strong national economies. Almost half of the new dams are located on just four rivers, i.e., 49 on the Chang Jiang (AS-32), 29 on the Rio de la Plata (SA-22), 26 on the Shatt Al Arab (AS-74), and 25 on the Ganges-Brahmaputra (AS-65) (*35*). New dams are also planned for several unaffected LRSs, including the Jequitinhonha (SA-16), Cá (AS-40), Agusan (AS-46), Rajang (AS-51), and Salween (AS-61). For each impact class, LRSs with weak economies (*36*) experience greater per-discharge population pressure (*37*) than economically strong LRSs, contributing to greater demand for dam construction among poorer basins. As in northern Canada, interbasin exchange of dam benefits will continue to influence decisions about dam construction. For example, more than 13 dams are planned or proposed for the currently unaffected Salween, the most imminent of which (the Tasang on the main stem) aims to provide international and interbasin benefits (*38*).

As noted, we excluded from our analysis most systems in Indonesia and several in Malaysia. This is unfortunate, because the region is one of the world's top three hotspots for biodiversity (*39*). Additionally, our definition of LRS depends solely on discharge, neglecting spatially large river systems in arid regions that carry little water on an annual basis (e.g., the Rio Grande in North America). Our classification features two limitations. First, it does not address within-basin variations in impacts, which could be substantial in large basins. For example, the moderately affected Mackenzie and Amazonas-Orinoco systems include extensive, virtually pristine areas as well as strongly affected areas. Second, our data often represent minima. We stopped gathering reservoir data once a system reached classification as strongly affected (although any outstanding dams are likely few and small).

As demands on water resources increase, our data can help address the ecological risks associated with further impacts on LRSs. For example, in free-flowing rivers, biodiversity can persist because organism dispersal can be effective in both upstream and downstream directions (*40*, *41*) and because many organisms are likely to adapt to climate change by concomitant shifts in distributions. But in fragmented and regulated rivers, such dispersal can be strongly limited (*10*). These facts need to be accounted for in global planning for sustainable river management.

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24. Following (*23, 25*), we synthesized our data on channel fragmentation and flow regulation to classify the river systems as strongly affected, moderately affected, or not affected (table S2). When reclassifying the northern 139 LRSs, we updated data on dams and excluded previously reported data on irrigation consumption. We excluded previously assessed irrigation data because a global, more consistent data set became available, which we analyzed for all 292 LRSs. We did, however, continue to consider data on interbasin diversions when reclassifying the northern LRSs, because no global and consistent data were available for analysis. Data on interbasin diversions for the 153 nonnorthern LRSs were largely unavailable and thus not considered during impact classification for those systems.
25. Information on materials and methods is available on *Science* Online.
26. Watershed boundaries were taken from (*42*) and modified in several cases to accommodate our definition of a river system. Operational navigation charts of the world (*43*) were consulted for boundary modifications.
27. D. M. Olson *et al.*, *Bioscience* **51**, 933 (2001).
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29. We calculated flow regulation as the sum of reservoir capacity within a river system [see (*25*) for data sources] and expressed this measure as the percentage of the LRS's volumetric annual discharge that can be contained and released by the reservoirs (live storage). One-half of the gross capacity was used as a substitute for live storage for reservoirs that lacked live storage data. The gross capacity is the total water volume that can be retained by a dam, including the bottom water that cannot be released through the lowest outlet. Live storage is the gross capacity excluding this bottom water.
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33. GLP was calculated in a first step as the basin sum of U.S. dollars assigned to each river system inhabitant according to his or her nationality (*44*) and corresponding 2003 per-capita gross domestic product (GDP) (*45*). We then divided this sum by VMAD (expressed in annual km^3), resulting in a per discharge GLP, referred to simply as GLP.
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35. "Rivers at Risk: Dams and the future of freshwater ecosystems" (World Wide Fund for Nature, Godalming, UK, 2004); available online at www.panda.org/downloads/freshwater/riversatriskfullreport.pdf.
36. We considered the minimum 2003 per-capita GDP of OECD member nations (*46*) as a cutoff between weak and strong economies. An LRS's economy was considered strong if its GLP (calculated per capita in this case, rather than per discharge) was greater than or equal to the cutoff. LRSs with GLPs lower than the cutoff were considered to have weak economies. (Mexico's per-capita GDP of $9300, second to lowest among all OECD member nations, was selected as the cutoff. Turkey represented the actual minimum, but data used to calculate Turkey's per-capita GDP were inconsistent with those used for the other OECD member nations; thus Turkey was excluded from selection.)
37. Population pressure was calculated as basin population (*44*) divided by VMAD (expressed in annual km^3).
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45. *The World Factbook* (U. S. Central Intelligence Agency, 2003); the current version is available online at www.cia.gov/cia/publications/factbook/index.html.
46. More information is available online at www.OECD.org.
47. We thank K. Berggren, E. Carlborg, P. Hansson, M. Svedmark, and S. Xiong for assistance with data collection; J. M. Helfield for valuable input on this manuscript; and S. L. Pimm for support. This work was economically supported by the Swedish WWF, the United Nations Educational, Scientific, and Cultural Organization/World Water Assessment Programme, the United Nations Environment Programme, and the World Resources Institute.

Supporting Online Material
www.sciencemag.org/cgi/content/full/308/5720/405/DC1
Materials and Methods
Tables S1 and S2

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Crystal Structure of the Malaria Vaccine Candidate Apical Membrane Antigen 1

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Apical membrane antigen 1 from *Plasmodium* is a leading malaria vaccine candidate. The protein is essential for host-cell invasion, but its molecular function is unknown. The crystal structure of the three domains comprising the ectoplasmic region of the antigen from *P. vivax*, solved at 1.8 angstrom resolution, shows that domains I and II belong to the PAN motif, which defines a superfamily of protein folds implicated in receptor binding. We also mapped the epitope of an invasion-inhibitory monoclonal antibody specific for the *P. falciparum* ortholog and modeled this to the structure. The location of the epitope and current knowledge on structure-function correlations for PAN domains together suggest a receptor-binding role during invasion in which domain II plays a critical part. These results are likely to aid vaccine and drug design.

Apical membrane antigen 1 (AMA1) is currently in clinical trials as a vaccine against *P. falciparum*, the species causing the most serious forms of malaria in humans. AMA1 is present in all *Plasmodium* species examined (*1*), and orthologs exist in other *Apicomplexa*, including *Toxoplasma* (*2*) and *Babesia* (*3*). Although little is known about its molecular function, genetic evidence indicates a role in maintaining parasite growth during the blood-stage cycle (*4*). Antibodies raised against AMA1 can inhibit erythrocyte invasion and protect against the disease in animal-model systems of malaria (*5–9*). Furthermore, invasion-inhibitory antibodies to AMA1 have been affinity-purified from human sera of donors from malaria-endemic regions (*10*). AMA1 is stored in the microneme organelles after synthesis and is translocated to the parasite surface just before or

Supporting Online Material

Materials and Methods

Sources of data on VMAD specifically for the US and Canada, Europe and former Soviet Union are presented in *S1*.

Data on VMAD for the 153 LRSs unassessed in *S1* were compiled from:

- F. van der Leeden, *Water resources of the world* (Geraghty & Miller, Inc., New York, 1975).
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- Swedish Meteorological and Hydrological Institute.
- The Global Runoff Data Centre, D - 56002 Koblenz, Germany (http://www.rivdis.sr.unh.edu/maps).
- United Nations Environment Programme, GEMS/WATER, Global Environment Monitoring System.
- World Wildlife Federation (http://www.worldwildlife.org).

Additional data on VMD for Mexico and Central America were compiled from:

- Association de Biologos y Ecologos de Nicaragua.
- Comision Nacional del Agua, Mexico.

Additional data on VMD for South America were compiled from:

- Agencia Nacional de Energia Electrica, Brazil.
- Centre d'ecologie des ressources renouvables, French National Centre for Scientific Research (CNRS).
- Comite Argentino de Grandes Presas, Argentina.
- Comité Venezolano de Grande Presas, Venezuela.
- Corporacion Nacional Forestal, Chile.
- Instituto de la Patagonia, Univ. de Magallanes, Chile.
- Instituto de Zoologia, Univ. Austral de Chile, Chile.
- Instituto Nacional de Meteorologica e Hidrologica, INAMHI, Ecuador.
- Meteorologia y Adecuacion de Tierras, Himat, Colombia.

Additional data on VMD for Asia (excluding Russia) and Australasia were compiled from:

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Table S1. Discharge, biogeographic diversity, fragmentation and regulation by dams, irrigation and economics of the world's largest river systems (LRSs). LRSs are grouped according to impact class within each continent (*S2, S3)*. The alpha-numeric labels before each river system refer to Fig. 1, beginning with a two-letter abbreviation for the continent of the river system's mouth followed by a number unique to the continent.

River System		VMAD*	Bio.†	Fragmentation Index‡		Reg.§	Irrig. **	Econ. ††
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
North and Central America – not affected								
NA 1	Colville	600	1	0	0	0	0	<1
NA 3	Coppermine	357	2	0	0	0	0	<1
NA 4	Back	612	2	0	0	0	0	<1
NA 5	Thelon, Kazan	1 370	2	0	0	0	0	5
NA 6	Thaanne, Thlewaitza	507	2	0	0	0	0	<1
NA 7	Seal	365	2	0	0	0	0	<1
NA 10	Hayes	694	1	0	0	0	0	2
NA 11	Severn	722	1	0	0	0	0	<1
NA 12	Winisk	694	1	0	0	0	0	<1
NA 13	Attawapiskat	626	1	0	0	0	0	<1
NA 16	Harricana	473	1	0	0	0	0	92
NA 18	Broadback	383	1	0	0	0	0	<1
NA 19	Rupert	878	1	0	0	0	0	<1
NA 23	Povungnituk	≥ 350	1	0	0	0	0	<1
NA 24	Arnaud	654	1	0	0	0	0	<1

	River System	VMAD* (m^3s^{-1})	Bio.[†]	Fragmentation Index[‡] Main Chann.	Tribs.	Reg.[§] (%)	Irrig. **	Econ. [††] (M USD km^{-3})
NA 25	R. Aux Feuilles	575	2	0	0	0	0	<1
NA 27	R. A La Baleíne	581	1	0	0	0	0	<1
NA 28	George	881	2	0	0	0	0	<1
NA 32	Petit Mécatina	524	1	0	0	0	0	<1
NA 33	Natashquan	422	1	0	0	0	0	<1
NA 34	Moisie	490	1	0	0	0	0	10
NA 54	Pascagoula	430	2	0	2	0.8	0	857
NA 58	Coatzacoalcos, Uspanapa	400	4	0	1	<1	1	211
NA 61	Patuca	800	4	0	0	0	1	82
NA 62	Coco (Segovia)	500	4	0	0	0	0	30
NA 63	Prinzapolca	700	3	0	0	0	0	19
NA 65	Escondido	800	4	0	0	0	2	19
NA 76	Skeena	1 760	2	0	2	0.1	0	18
NA 77	Nass	892	4	0	0	0	0	8
NA 78	Stikine	1 600	4	0	0	0	0	4
NA 79	Taku	600	4	0	0	0	0	13
NA 80	Alsek	800	4	0	1	2	0	1
NA 81	Copper	1 700	4	0	0	0	0	4
NA 82	Susitna	1 400	3	0	0	0	0	37

	River System	VMAD* (m^3s^{-1})	Bio.[†]	Fragmentation Index[‡] Main Chann.	Fragmentation Index[‡] Tribs.	Reg.[§] (%)	Irrig. **	Econ. [††] (M USD km^{-3})
NA 83	Kvichak	590	2	0	0	0	0	1
NA 84	Nushagak	1 000	3	0	0	0	0	<1
NA 85	Kuskokwim	1 900	2	0	0	0	0	6
NA 86	Yukon	6 370	3	0	2	0.05	0	25
NA 87	Kobuk	510	2	0	0	0	0	6
NA 88	Noatak	≥ 350	2	0	0	0	0	<1
<u>North and Central America: moderately affected</u>								
NA 2	MacKenzie	9 910	5	1	1	12	0	39
NA 14	Albany	1 420	1	1	2	1.5	0	5
NA 17	Nottaway	1 130	2	0	2	>0	0	58
NA 22	Gr. R. Baleíne	665	1	0	1	>0	0	<1
NA 36	R. aux Outardes	399	1	1	0	10.5	0	12
NA 45	Delaware	550	2	1	2	5	9	12 356
NA 46	Susquehenna	1 198	2	2	2	2	2	4 738
NA 47	Potomac	≥ 350	1	3	1	1.5	3	11 945
NA 48	Pee Dee	552	2	3	1	4	4	4 077
NA 51	Altamaha	406	2	1	2	4	54	6 114
NA 56	Panuco	500	5	1	2	10	214	6 715
NA 59	Usumacinta, Grijalva	3 000	4	1	2	12	8	556

	River System	VMAD* (m^3s^{-1})	Bio.†	Fragmentation Index‡ Main Chann.	Tribs.	Reg.§ (%)	Irrig. **	Econ. †† (M USD km^{-3})
NA 60	Ulua	550	3	0	2	39	31	479
NA 64	Grande de Matagalpa	500	4	1	2	2	7	183
NA 66	San Juan	600	5	0	2	11	31	659
NA 74	Skagit	475	1	2	1	8	12	1 208
NA 75	Fraser	3 620	2	0	2	13	0	364
North and Central America: strongly affected								
NA 8	Churchill	1 270	3	2	2	47	0	78
NA 9	Nelson	2 830	5	3	2	90	38	1 910
NA 15	Moose	1 440	2	3	2	7	0	84
NA 20	Eastmain	909	1	1	2	12	0	<1
NA 21	La Grande	1 720	1	3	1	96	0	<1
NA 26	Koksoak	2 420	1	2	0	51	0	<1
NA 29	Kanairiktok	≥ 350	1	1	0	>0	0	<1
NA 30	Naskaupi	≥ 350	1	2	0	>0	0	<1
NA 31	Churchill	1 620	1	3	2	61	0	20
NA 35	Manicouagan	852	1	3	1	295	0	35
NA 37	Betsiamites	375	1	2	0	59	0	7
NA 38	Saguenay	1 760	2	3	1	14.5	0	149
NA 39	St. Lawrence	10 800	4	3	2	11	9	4 780

	River System	VMAD*	Bio.[†]	Fragmentation Index[‡]		Reg.[§]	Irrig. **	Econ. [††]
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
NA 40	St. John	1 100	2	3	2	2.5	1	380
NA 41	Penobscot	450	1	3	2	8	1	417
NA 42	Kennebec, Androscoggin	488	1	3	2	7.5	0	756
NA 43	Conneticut	540	1	4	2	9	6	4 673
NA 44	Hudson	620	1	2	2	10	3	13 591
NA 49	Santee	560	2	3	2	30	5	6 530
NA 50	Savannah	369	2	3	2	48	17	4 913
NA 52	Apalachicola	750	2	3	1	11	74	6 665
NA 53	Alabama, Mobile	1 900	2	4	2	6.5	2	2 423
NA 55	Mississippi	18 400	5	3	2	15.5	185	4 698
NA 57	Papaloapan, San Juan	650	4	3	2	34	29	630
NA 67	Lempa	400	4	3	0	15	14	574
NA 68	Balsas	500	5	1	2	41	381	14 559
NA 69	Río Grande de Santiago	390	6	3	2	49	906	12 622
NA 70	Colorado	550	4	3	2	280	990	20 728
NA 71	Sacramento, San Joaquín	1 140	4	2	2	49	828	11 281
NA 72	Klamath	515	1	3	2	15.5	70	592
NA 73	Columbia	7 500	4	4	2	24	118	1 034

River System		VMAD* (m^3s^{-1})	Bio.†	Fragmentation Index‡		Reg.§ (%)	Irrig. **	Econ. †† (M USD km^{-3})
				Main Chann.	Tribs.			
South America: not affected								
SA 1	Atrato	2 274	3	0	0	0	0	93
SA 4	Catatumbo	470	5	0	0	0	62	1 405
SA 5	Essequibo	2 213	2	0	0	0	1	8
SA 6	Courantyne	1 500	2	0	0	0	6	8
SA 7	Coppename	500	2	0	0	0	23	13
SA 8	Maroni (Suriname)	2 500	2	0	2	≤1	0	16
SA 9	Oyapock	900	1	0	0	0	0	6
SA 12	Gurupi	470	3	0	0	0	1	177
SA 16	Jequitinhonha	425	4	0	2	0.6	8	1 094
SA 24	Santa Cruz	666	3	0	0	0	0	2
SA 25	Pascua	574	3	0	0	0	0	1 357
SA 26	Baker	950	3	0	0	0	0	4
SA 27	Palena	≥ 350	2	0	0	0	0	4
SA 29	Puelo	670	1	0	0	0	0	4
SA 30	Bueno	≥ 350	2	0	0	0	4	515
SA 31	Valdivia	450	2	0	0	0	1	150
SA 35	Esmeraldas	700	3	0	0	0	26	205
SA 36	Santiago, Cayapas	403	2	0	0	0	24	139

	River System	VMAD*	Bio.†	Fragmentation Index‡		Reg.§	Irrig. **	Econ. ††
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
SA 37	Patia	≥ 350	3	0	1	<1	17	854
SA 38	San Juan	1 991	3	0	≥1	0	7	19
South America: moderately affected								
SA 2	Sinú	385	4	2	0	10	35	579
SA 3	Magdalena	7 500	5	1	2	1	22	540
SA 10	Araguari	967	2	2	0	1	0	18
SA 11	Amazonas, Orinoco	200 000	8	0	2	3	1	41
SA 13	Mearim, Grajaú, Pindaré	429	3	0	1	4	8	553
SA 14	Parnaiba	1 000	4	2	1	10	11	1 179
SA 17	Doce	1 000	3	1	1	0.4	10	620
SA 19	Juquiá, Ribeira	≥ 350	3	0	2	2	3	177
SA 20	Itajai	370	1	1	2	3	20	768
SA 28	Futaleufu	550	1	2	0	16	0	2
SA 32	Bío-Bío‡‡	900	4	2	2	7	92	140
SA 34	Guayas	835	5	0	2	11	135	530
South America: strongly affected								
SA 15	Sao Francisco	2 800	5	2	≥1	37	41	1 561
SA 18	Paraiba do Sul	876	3	3	2	20	50	1 587

	River System	VMAD*	Bio.[†]	Fragmentation Index[‡]		Reg.[§]	Irrig. **	Econ. [††]
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
SA 21	Jacuí, Camaquã, Jagarão	2 000	2	3	2	4	29	645
SA 22	Río de la Plata	21 000	6	3	2	28	25	947
SA 23	Río Negro	900	3	2	2	140	45	290
SA 33	Itata, Maule	500	3	3	2	10	271	418
Europe: not affected								
EU 10	Kalixälven, Torneälven	373	2	0	≤1	1	0	241
EU 12	Onega	500	1	0	0	0	0	138
EU 14	Mezen	880	2	0	0	0	0	11
EU 15	Pechora	4 100	2	0	0	0	0	45
EU 29	Adour[‡‡]	360	1	0	2	0.7	82	1960
Europe: moderately affected								
EU 1	Ölfusá	440	2	0	2	1.2	0	12
EU 13	Severn, Dvina	3 330	1	1	0	1	0	183
EU 17	Rioni	420	1	2	1	<1	251	303
EU 18	Kuban[‡‡]	430	2	≥1	≥1	23	809	2612
EU 31	Loire	900	2	1	2	1.5	150	7 463
EU 32	Seine	500	1	1	2	2.5	168	25 489
EU 33	Rhein, Maas	2 200	2	≤2	2	5	48	20 714

	River System	VMAD* (m^3s^{-1})	Bio.[†]	Fragmentation Index[‡]		Reg.[§] (%)	Irrig. **	Econ. [††] (M USD km^{-3})
				Main Chann.	Tribs.			
EU 36	Oder	580	2	2	2	5	27	8 567
EU 37	Wisla	1 080	2	2	2	4	15	6 465
EU 40	Narva	450	2	1	0	<1	2	638
Europe: strongly affected								
EU 2	Thjórsá	390	2	3	2	13	0	8
EU 3	Glommavassdr.	728	3	4	2	16	23	1 985
EU 4	Göta Älv	554	4	3	2	27	14	1 887
EU 5	Dalälven	353	3	3	2	26	0	926
EU 6	Indalsälven	448	2	4	2	40	0	189
EU 7	Ångermanälven	481	2	4	2	43	0	138
EU 8	Umeälven	435	2	4	1	27	0	283
EU 9	Luleälven	500	2	3	2	72	0	57
EU 11	Kemijoki	553	1	2	1	23	0	193
EU 16	Volga	8 050	4	4	2	34	56	2 166
EU 19	Don	890	2	≥1	≥1	51	309	5 672
EU 20	Dnepr	1 700	2	≥3	1	35	669	3 349
EU 21	Danube	6 450	4	3	2	4.6	3	4 965
EU 22	Drin	≥350	2	≥3	2	19.5	0	603
EU 23	Neretva	378	2	3	2	7	1225	164

	River System	VMAD*	Bio.†	Fragmentation Index‡		Reg.§	Irrig. **	Econ. ††
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
EU 24	Po	1 460	3	3	2	4	72	11 443
EU 25	Rhone	1 900	3	4	2	5.5	117	4 470
EU 26	Ebro	577	2	4	2	23	252	3 302
EU 27	Tajo (Tejo)	500	2	4	2	25	418	9 209
EU 28	Duero (Douro)	650	2	3	2	31	43	4 815
EU 30	Garonne, Dordogne	1 045	2	3	2	6.45	106	2 973
EU 34	Weser	360	1	4	2	2.5	148	23 916
EU 35	Elbe	750	1	2	2	12.5	88	19 529
EU 38	Nemunas	620	1	3	2	1	8	2 329
EU 39	Daugava	640	1	3	2	1	4	1 166
EU 41	Neva	2 490	3	3	2	17	4	1 066
Asia: not affected								
AS 2	Nadym	610	1	0	0	0	0	29
AS 3	Pur	1050	2	0	0	0	0	97
AS 4	Taz	1540	2	0	0	0	0	3
AS 6	Pyasina	2260	2	0	0	0	0	22
AS 7	Taymyra	990	1	0	0	0	0	<1
AS 8	Khatanga, Popigay	3200	2	0	0	0	0	<1
AS 9	Anabar	432	2	0	0	0	0	2

	River System	VMAD*	Bio.†	Fragmentation Index‡		Reg.§	Irrig. **	Econ. ††
		(m^{3}s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
AS 10	Olenek	1090	2	0	0	0	0	<1
AS 12	Yana	970	2	0	0	0	0	7
AS 13	Indigirka	1700	2	0	0	0	0	4
AS 15	Anadyr	2020	2	0	0	0	0	1
AS 16	Penzhina	720	1	0	0	0	0	3
AS 17	Kamchatka	1050	2	0	0	0	0	3
AS 18	Tauy	362	2	0	0	0	0	<1
AS 19	Uda	800	2	0	0	0	0	2
AS 39	Mã	637	2	0	0	0	12	518
AS 40	Cá, Chu	767	1	0	0	0	39	435
AS 43	Abra	398	2	0	0	0	43	156
AS 46	Agusan	884	1	0	0	0	0	227
AS 48	Kinabatangan	840	3	0	2	0	14	131
AS 49	Baram	827	1	0	0	0	0	63
AS 50	Kemena	372	2	0	0	0	0	85
AS 51	Rajang	3 260	2	0	2	0	5	62
AS 53	Pahang	874	1	0	2	<1	14	1 341
AS 55	Kelantan	536	1	0	1	<1	0	264
AS 59	Great Tenasserim	1 778§§	2	0	0	0	0	5

	River System	VMAD*	Bio.[†]	Fragmentation Index[‡]		Reg.[§]	Irrig. **	Econ. [††]
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
AS 60	Tavoy	484[§§]	1	0	0	0	0	48
AS 61	Salween (Thanlwin)	5 250	6	0	2	0.3	6	95
AS 63	Kaladan	3 476[§§]	1	0	0	0	0	10
<u>Asia: moderately affected</u>								
AS 1	Ob	12800	7	2	2	9	30	580
AS 11	Lena	16900	4	0	1	3	0	23
AS 14	Kolyma	4060	2	1	0	5	0	2
AS 20	Amur	10900	8	0	2	9	62	967
AS 21	Ishikari Gawa	468	2	1	2	6	0	4 888
AS 22	Mogami Gawa	392	2	2	2	2	27	2 463
AS 23	Shinano Gawa	514	2	2	2	1	78	4 122
AS 24	Agano Gawa[‡‡]	417	2	2	2	9	104	2 483
AS 35	Min Jiang[‡‡]	1 870	1	≥2	2	4	73	834
AS 36	Han Jiang[‡‡]	828	1	≥1	2	10	67	1 277
AS 38	Hong Ha (Red River)	3 900	2	0	2	3	63	2 375
AS 41	Boung, Thu Bon, Cái	611	2	1	2	<1	26	164
AS 42	Mekong	15 900	5	2	2	3	39	457
AS 44	Cagayan	1 710	2	0	2	1.5	35	254
AS 47	Mindanao	852	1	2	0	0.2	18	436

	River System	VMAD* (m^3s^{-1})	Bio.†	Fragmentation Index‡ Main Chann.	Tribs.	Reg.§ (%)	Irrig. **	Econ. †† (M USD km^{-3})
AS 52	Bengwan Solo	463	1	0	2	5	192	2 897
AS 56	Mae Nam Ta Pi	397	2	0	1	38	27	570
AS 62	Irrawaddi (Ayeyarwadi)	11 953	7	0	2	1.1	42	176
AS 64	Karnafuli	4 751	2	2	0	3	0	111
AS 65	Ganges, Brahmaputra	22 102	10	1	1	8	357	2 024
<u>Asia: strongly affected</u>								
AS 5	Yenisey	20000	8	≥2	2	18	0	101
AS 25	Kiso, Ibi, Nagara Gawa	350	2	3	2	8	174	21 070
AS 26	Nakton Gang	442	1	3	2	21	263	10 087
AS 27	Han Gang	615	1	3	2	29	81	10 497
AS 28	Yalu Jiang	1 200	1	2	2	39	68	588
AS 29	Liao He	400	3	1	2	26	1033	13 407
AS 30	Hai He	723	3	3	2	68	2194	19 008
AS 31	Huang He (Yellow)	1990	6	3	2	51	911	9 897
AS 32	Chang Jiang (Yangtze)	29460	4	2	2	12	148	2 023
AS 33	Qiantan Jiang	1160	2	3	2	37	265	3 086
AS 34	Ou Jiang	599	1	2	2	12	62	1 199
AS 37	Zhu Jiang (Pearl)	10 700	1	3	2	31	68	1 107

	River System	VMAD* (m^3s^{-1})	Bio.[†]	Fragmentation Index[‡] Main Chann.	Tribs.	Reg.[§] (%)	Irrig. **	Econ. [††] (M USD km^{-3})
AS 45	Pampanga	≥ 350	1	1	2	24	162	4 785
AS 54	Perak	480	1	3	2	11	16	994
AS 57	Chao Phraya	961	3	2	2	76	581	4 208
AS 58	Mae Khlong	425	3	3	2	130	193	525
AS 66	Mahanadi, Brahmani	2 125	3	3	2	17	389	1 828
AS 67	Krishna, Godavari	3 053	3	2	2	37	730	3 968
AS 68	Cauvery	666	3	3	2	19	772	3 806
AS 69	Periyar	390	2	3	1	46	122	1 335
AS 70	Tapi	444	4	3	2	54	621	2 388
AS 71	Narmada	1 490	4	2	2	26	392	1 072
AS 72	Mahi	383	1	3	2	15	371	1 367
AS 73	Indus	6 564	8	3	2	13	1173	1 974
AS 74	Shatt Al Arab (Euphrates-Tigris)	1750	6	2	2	124	1138	3 327
AS 75	Kura	850	5	≥3	2	44	734	2 294
AS 76	Amu-Dar'Ya	2200	5	≥1	2	14	610	676
AS 77	Syr-Dar'Ya	1170	5	≥3	2	55	1187	2 100
AS 78	Ili	570	5	≥2	≥1	37	321	1 307
Africa: not affected								
AF 2	Rufiji	820	5	0	≤2	0	14	115

	River System	VMAD* ($m^3 s^{-1}$)	Bio.[†]	Fragmentation Index[‡] Main Chann.	Tribs.	Reg.[§] (%)	Irrig. **	Econ. [††] (M USD km^{-3})
AF 4	Tsiribihina	1 000	4	0	0	0	40	35
AF 5	Mangoky	460	5	0	0	0	105	43
AF 12	Kouilou	930	2	0	0	0	0	20
AF 13	Nyanga	≥ 350	2	0	0	0	0	24
AF 15	Ntem	400	1	0	0	0	0	59
AF 17	Cross	550	3	0	2	0	1	429
AF 21	Cavally	≥ 350	1	0	0	0	0	57
AF 24	Chari	1 200	5	0	0	0	7	418
Africa: moderately affected								
AF 3	Betsiboka	440	2	1	1	2	85	161
AF 7	Save	750	5	0	2	10	11	278
AF 10	Cuanza	830	2	2	1	10	3	167
AF 11	Congo (Zaire)	41 000	6	1	2	0	0	34
AF 14	Ogooué	4 700	3	1	1	≤25	0	20
AF 16	Sanaga	2 070	2	2	≥1	10	0	139
AF 22	Konkouré	1 170	3	0	≤2	4	4	61
Africa: strongly affected								
AF 1	Nile	3 000	6	3	2	95	393	3 319
AF 6	Zambezi	7 070	8	2	2	30	8	186

	River System	VMAD*	Bio.[†]	Fragmentation Index[‡]		Reg.[§]	Irrig. **	Econ. [††]
		(m^3s^{-1})		Main Chann.	Tribs.	(%)		(M USD km^{-3})
AF 8	Limpopo	2 000	5	3	2	5	45	2 196
AF 9	Orange	2 900	4	3	2	14	45	1 235
AF 18	Niger	6 100	6	3	2	15	21	372
AF 19	Volta	1 120	3	3	2	428	5	812
AF 20	Sassandra	425	2	2	0	31	14	372
AF 23	Sénégal	770	3	2	0	24	52	321
Australasia: not affected								
AU 1	Timoforo, Kamoendan	≥ 350	2	0	0	0	0	20
AU 2	Derewo, Owa	≥ 350	3	0	0	0	0	5
AU 3	Mamberamo	4 500	3	0	0	0	0	6
AU 4	Sepik	3 804	2	0	0	0	0	16
AU 6	Markham	546	2	0	0	0	0	33
AU 7	Purari	2 571	3	0	0	0	0	20
AU 8	Kikori	3 274	3	0	0	0	0	8
AU 9	Turama	988	2	0	0	0	0	1
AU 10	Fly	6 000	3	0	0	0	0	1
AU 11	Merauke	≥ 350	3	0	0	0	0	29
AU 12	Bian	≥ 350	3	0	0	0	0	10
AU 13	Digul	≥ 350	3	0	0	0	0	36

	River System	VMAD* (m^3s^{-1})	Bio.†	Fragmentation Index‡		Reg.§ (%)	Irrig. **	Econ. †† (M USD km^{-3})
				Main Chann.	Tribs.			
AU 14	Eilanden, Lorentz, Kampong, Nordwest	≥ 350	3	0	0	0	0	18
AU 15	Omba	≥ 350	2	0	0	0	0	2
AU 16	Laluai	1 612	1	0	0	0	0	<1
AU 19	Grey	353	2	0	0	0	3	5
AU 20	Buller	488	2	0	0	0	1	21
Australasia: moderately affected								
AU 5	Ramu	1 500	3	1	≤2	0.4	0	22
AU 23	Waiau	512	2	2	0	5	0	4
Australasia: strongly affected								
AU 17	Murray	775	6	1	2	67	644	4 345
AU 18	Waikato	417	1	3	2	1	4	509
AU 21	Waitaki	367	3	2	2	32	30	20
AU 22	Clutha	563	3	3	2	7	61	37

* Virgin mean annual discharge (VMAD) refers to the most water-rich river channel section, in most cases close to the estuary, before any significant direct human manipulation.

† The number of non-marine biomes (*S4*) represented within the river system's catchment area.

‡ For the main channel, fragmentation is ranked into five classes describing the longest portion of the main-channel left without dams (but frequently including reservoir water tables) in relation to the entire main channel (0 = 100%; 1 = 75—99%; 2 = 50—74%; 3 = 25—49%; and 4 = 0—24%). The main channel is the channel having the highest VMAD. For the tributaries, fragmentation is described by three classes (0 = no dams; 1 = dams only in the catchment of minor tributaries; 2 = dams in the catchment of the largest tributary).

§ Readers are advised that all values are estimates and sometimes minimums, especially for systems in the strongly affected class. Specific live and gross storage capacities were reported for the 139 northern systems (*S1*) and those values were used in derivation of the values reported here (*S5*). Classifications dependent on previous interbasin diversion data (*S1*) are reported unchanged here, although reservoir storage data alone do not meet the criteria for the assigned impact classes for five systems (NA-17, 20, 22, 29, 30). Classifications dependent on previous irrigation data (*S1*) were reclassified according to reservoir storage data alone – this applies to the Kuban (EU-18) and Adour (EU-29) systems which each dropped one impact class. Flow regulation presented for the Hudson (NA-44) reflects a correction of previous data (*S1*) which resulted in higher impact classification. Values presented for the Ebro (EU-26), Tajo (EU-27) and Duero (EU-28) also reflect corrections (*S1*), although impact classification did not change as a result.

** The irrigation index was calculated as the ratio of km^2 equipped for or under irrigation (*S6*) to VMAD (in km^3), presented as a unitless index. This index suggests that the higher the value, the greater the pressure that irrigation could exert on the system. Values of zero describe systems with negligible land equipped for or under irrigation.

†† Economic activity is described as 'Per Discharge Gross LRS Product' (GLP) (*S7*). This index implies that the higher the value, the greater the economic activity per unit of water in the system.

‡‡ These six systems may actually have a flow that is more impacted than is suggested by the impact class, because the fragmentation and flow regulation data nearly meet criteria for the next highest impact class and additional irrigation pressure is high.

§§ These VMAD values were estimated using an environmental model (*S8*).

Table S2. Principles for constructing three classes of river system exploitation (not affected, moderately affected, and strongly affected) from the combination of fragmentation and flow regulation assessments (*S1*). The fragmentation classes are defined in Table S1. Summed values of reservoir live storages are given as the percentage of VMAD and shown as flow regulation (Table S1). Where data on live storage were lacking, half the gross capacity was used as a substitute.

Fragmentation (Main channel + tributaries)	Flow regulation (%)		
	Not affected	Moderately affected	Strongly affected
0 + 0	0		
0 + 1	≤ 2	> 2	
0 + 2	≤ 1	> 1	
1 + 0		≤ 30	> 30
1 + 1		≤ 25	> 25
1 + 2, 2 + 0		≤ 20	> 20
2 + 1		≤ 15	> 15
2 + 2, 3 + 0		≤ 10	> 10
3 + 1		≤ 5	> 5
3 + 2, 4 + 0, 1, 2			≥ 0

References

S1. M. Dynesius, C. Nilsson, Science 266, 753 (1994).

S2. T. Simkin, J.D. Unger, R.I. Tilling, P.R. Vogt, H. Spall, “This Dynamic Planet – World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics” (Smithsonian Institution and U.S. Geological Survey, 1994). [http://pubs.usgs.gov/pdf/planet.html].

S3. The Times Atlas of the World - Comprehensive ed. (Times Books, London, 1997).

S4. D. M. Olson et al. BioScience 51, 933 (2001).

S5. We calculated flow regulation as the sum of reservoir capacity within a river system (see Materials and Methods for data sources) and expressed this measure as the percentage of the LRS’s volumetric annual discharge that can be contained and released by the reservoirs (live storage). One half of the gross capacity was used as a substitute for live storage for reservoirs which lacked live storage data. The gross capacity is the total water volume that can be retained by a dam, including the bottom water that cannot be released through the lowest outlet. Live storage is the gross capacity excluding this bottom water.

S6. S. Siebert, P. Döll, J. Hoogeveen, “Global map of irrigated areas version 2.0” (Center for Environmental Systems Research, Univ. of Kassel, Germany and Food and Agriculture Organization of the United Nations, Rome, Italy, 2001).

S7. GLP was calculated in a first step as the basin sum of US dollars assigned to each river system inhabitant according to his/her nationality (S9) and corresponding 2003 per capita gross domestic product (S10). We then divided this sum by VMAD (expressed in annual km3), resulting in a ‘per discharge’ GLP, referred to simply as GLP.

S8. P. Schreiber, Meteorol. Zeitschr. 21, 441 (1904).

S9. “Population LandScan 2000 global population database” (Oakridge, TN: Oak Ridge National Laboratory) [http://sedac.ciesin.columbia.edu/plue/gpw/landscan].

S10. The World Factbook (United States Central Intelligence Agency, 2003) [http://www.cia.gov/cia/publications/factbook/index.html].