High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management

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Despite the recognized importance of reservoirs and dams, global datasets describing their characteristics and geographical distribution are largely incomplete. To enable advanced assessments of the role and effects of dams within the global river network and to support strategies for mitigating ecohydrological and socioeconomic costs, we introduce here the spatially explicit and hydrologically linked Global Reservoir and Dam database (GRanD). As of early 2011, GRanD contains information regarding 6862 dams and their associated reservoirs, with a total storage capacity of 6197 km^3. On the basis of these records, we estimate that about 16.7 million reservoirs larger than 0.01 ha – with a combined storage capacity of approximately 8070 km^3 – may exist worldwide, increasing Earth's terrestrial surface water area by more than 305 000 km^2. We find that 575 900 river kilometers, or 7.6% of the world's rivers with average flows above 1 cubic meter per second (m^3 s^{-1}), are affected by a cumulative upstream reservoir capacity that exceeds 2% of their annual flow; the impact is highest for large rivers with average flows above 1000 m^3 s^{-1}, of which 46.7% are affected. Finally, a sensitivity analysis suggests that smaller reservoirs have substantial impacts on the spatial extent of flow alterations despite their minor role in total reservoir capacity.

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Humans have built dams and impoundments for thousands of years for various purposes, including flood control, water supply, irrigation, recreation, navigation, and the generation of hydropower (WCD 2000). Yet the number and storage volumes of dams and reservoirs have increased markedly over the past six decades, today reaching about 50 000 large dams – defined as those higher than 15 m – in operation worldwide (Berga *et al.* 2006). These impoundments are estimated to have a cumulative storage capacity in the range of 7000 to 8300 km^3 (Vörösmarty *et al.* 2003; Chao *et al.* 2008); this compares to the combined volumes of Lakes Michigan and Huron, or nearly 10% of the water stored in all natural freshwater lakes on Earth (Gleick 2000), and represents about one-sixth of the total annual river flow into the oceans (Hanasaki *et al.* 2006). Smaller impoundments are not taken into account in these estimates because there are no reliable global figures available. Extrapolations, however, suggest that many such impoundments exist (Downing *et al.* 2006; Wisser *et al.* 2010), including several million small dams in the US alone (Renwick *et al.* 2005).

Dams and reservoirs play an important role in the control and management of water resources. Undoubtedly, mitigating floods, securing water supplies, and providing hydropower have benefited human societies in many ways, allowing for improved human health, expanded food production, and economic growth. For example, large dams are estimated to contribute directly to 12–16% of global food production (WCD 2000). Recent projections suggest that 70% more food will be needed by 2050 (nearly 100% in developing countries) to cope with a 40% increase in world population and to accommodate expected shifts in global dietary patterns (Bruinsma 2009); part of that additional food will be produced on irrigated lands that will

In a nutshell:

- For thousands of years, reservoirs and dams have been built to benefit human society, and their numbers have increased markedly over the past 60 years
- Dams disrupt the ecological connectivity of rivers, whereas reservoirs' water storage and release patterns affect quantity, quality, and timing of downstream flows
- To assess related local and global impacts, scientists and managers require comprehensive and spatially explicit information about the location, size, and purpose of dams and reservoirs within the river network
- The Global Reservoir and Dam database (GRanD) will advance ecohydrological studies and assist sustainable flow-management strategies, such as the implementation of environmental flow standards or the prioritization of adaptive dam operations

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require 11% more water, much of it likely to come from storage reservoirs. Additionally, hydropower provides about 19% of the world's electricity supply and is used in more than 150 countries (WCD 2000).

On the other hand, dams and reservoirs, especially large ones, can induce substantial costs to human societies, exemplified by displacement/resettlement, social disruption, changes in water and food security, and increased incidence of communicable diseases (Scudder 2006). In terms of environmental effects, flow regulation is considered one of the main adverse ecological consequences of dams and reservoirs (Poff *et al.* 1997; Bunn and Arthington 2002). The goal of many dam operations is to eliminate peak flows, to stabilize low flows, or to impound or divert river flows partially or entirely. These alterations lead to numerous physical and ecological impacts on freshwater, terrestrial, and marine ecosystems and their dependent species (Pringle *et al.* 2000; Dudgeon *et al.* 2006; Freeman and Marcinek 2006; Carlisle *et al.* 2011).

Many riverine species are adapted to, and synchronized with, specific river flow patterns, such as spring peak floods or summer low flows. These patterns cue species to reproduce, disperse, migrate, feed, and avoid predators; alterations to natural flow patterns may disrupt life cycles and ecological processes. To mitigate negative effects, ecologists and water resource planners are increasingly interested in the adaptation of dam operations toward releasing "environmental flows" (ie an appropriate "quantity, quality, and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems"; Brisbane Declaration 2007). In particular, given that the downstream effects of flow alterations can be far reaching, the ELOHA framework (Ecological Limits of Hydrologic Alteration; Poff *et al.* 2010) explicitly calls for regional-scale hydrologic modeling and analyses to inform environmental flow management, when lack of time and resources preclude evaluating individual rivers and locations.

Beyond flow regulation, dams also fragment aquatic habitats (Jansson *et al.* 2000; Nilsson *et al.* 2005), impeding not only the movement of species but also the delivery of nutrients and sediments downstream. By decreasing sediment transport, dams reduce the riverine habitat-forming substrate available for critical life stages, such as fish nesting and refuge (Černý *et al.* 2003). Reduced sediment and nutrient transport also affects estuarine and coastal communities (Syvitski *et al.* 2005; Baisre and Arboleya 2006; Ericson *et al.* 2006). Many river deltas, for instance, are sinking as a result of reduced sediment delivery, thereby increasing the vulnerability of human populations depending on their ecosystem services for survival (Syvitski *et al.* 2009). Furthermore, flood attenuation reduces the rich productivity of natural floodplains (Arthington and Welcomme 1995; Tockner *et al.* 2008), putting at risk millions of people relying on them for their livelihoods (Richter *et al.* 2010). Similar to that of sediments, the distribution, trapping, or accumulation of contaminants in river systems is modified by dam obstruction and reservoir retention.

Shiklomanov (2000) has estimated that the additional water lost as a result of reservoir-based evaporation amounts to about 5% of total global river flows, thus exceeding industrial and domestic water consumption combined, which can greatly contribute to diminishing water resources in some regions. Also, the increased water storage in the world's reservoirs may collectively be responsible for a measurable delay in sea-level rise (Chao *et al.* 2008); hence, detailed knowledge of the global extent of reservoirs over time is important for improving climate-change-related risk assessments. Smaller reservoirs are increasingly of concern to researchers because their cumulative effects may be considerable, yet they have so far remained underemphasized and unexamined (Downing *et al.* 2006). For example, Harrison *et al.* (2009) showed that small reservoirs play an important regional and global role in the removal of nitrogen from surface water. Finally, although hydropower is often perceived and promoted as "green" energy, reservoirs are estimated to be responsible for at least 4% of human-induced global warming in the form of greenhouse-gas emissions (eg methane; St Louis *et al.* 2000; Lima *et al.* 2008). In a recent study, Del Sontro *et al.* (2010) found that temperate reservoirs, under certain circumstances, may have higher methane emission rates than expected, especially in a warming climate; they concluded that a more detailed analysis of the biogeochemical and geographical setting of reservoirs is needed.

Given these concerns, there is widespread agreement in the ongoing sustainable dam management/planning debate about the importance of better assessing the role and effects of dams and reservoirs (eg WCD 2000) and of minimizing associated societal and environmental costs while leveraging the benefits. Scientific research is recognized to provide critical input to this debate but, unfortunately, inadequate data and assessment tools – particularly at regional and global scales – have previously hindered the advancement of new and rigorous studies.

In this paper, we offer three contributions to promote this dialogue. First, we introduce a new global dam and reservoir database, at unprecedented spatial resolution, to serve as the backbone for a suite of new assessments. Second, by conducting extrapolations from this database, we provide robust estimates of the number and storage capacities of small reservoirs worldwide, which can inform subsequent ecological assessments. Third, by using the database in a pilot study to demonstrate its capability, we present spatially detailed calculations of the degree of flow regulation caused by dams. As a result, we create a first-time global risk map of potential impacts of reservoir clusters on downstream flow regimes at the resolution of individual river reaches.

A new global reservoir and dam database

Despite the many critical environmental and social tradeoffs associated with dams and reservoirs, global datasets

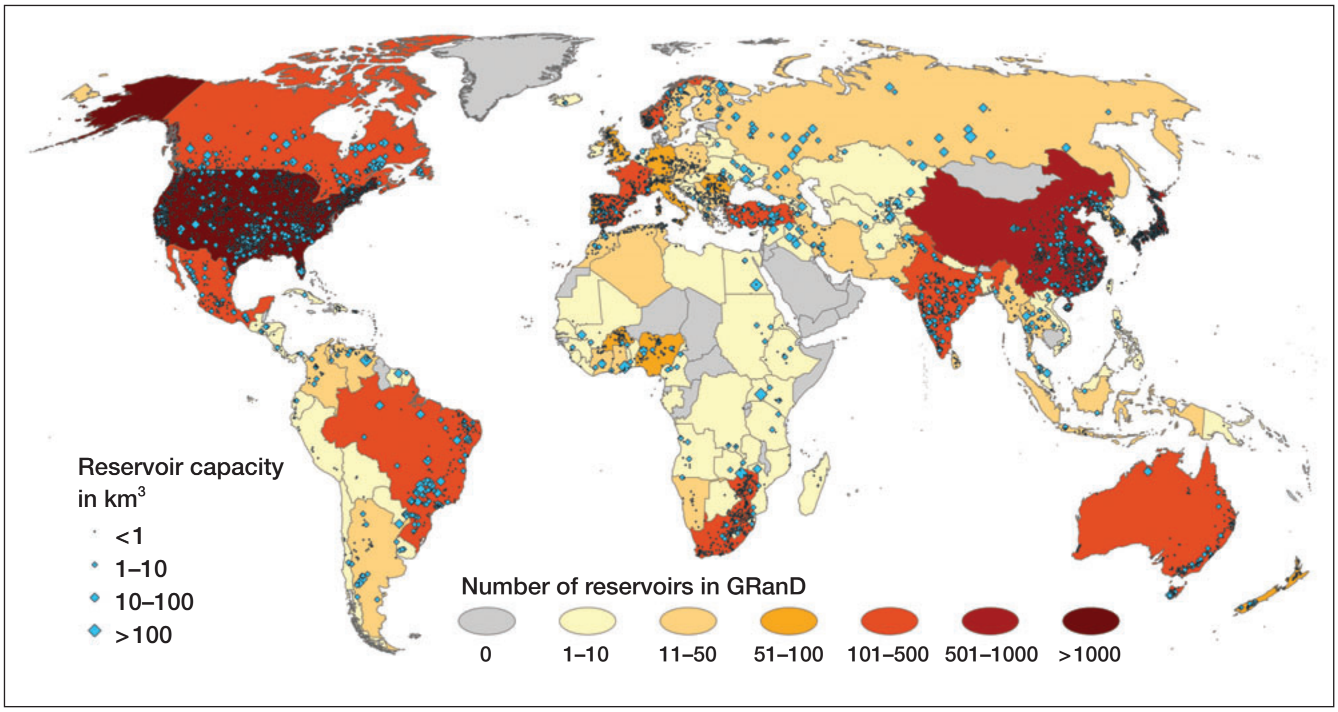

Figure 1. *Global distribution (by country) of large reservoirs included in GRanD.*

describing their characteristics and geographical distribution have heretofore been largely incomplete (see WebPanel 1 and WebTable 1). To address this shortcoming, the Global Water System Project, a collaborative project of the Earth System Science Partnership, initiated an international effort to collate existing dam and reservoir datasets, with the aim of providing a single, geographically explicit and reliable database for the scientific community: the Global Reservoir and Dam database (GRanD). For technical details of the data development, see WebPanel 1.

The current version 1.1 of GRanD contains 6862 records of reservoirs and their associated dams (Figure 1), with a cumulative storage capacity of 6197 km^3. The largest combined volumes are concentrated in Canada, Russia, the US, Brazil, and China (WebTable 2). GRanD's attribute data include (in most cases) the dam and reservoir names, spatial coordinates, construction year, surface area, storage capacity, dam height, main purpose, and elevation. Up- and downstream topology was introduced by linking GRanD to HydroSHEDS, a near-global, high-resolution digital river network (Lehner *et al.* 2008). This linkage allowed for the derivation of additional attributes, such as the contributing catchment area for each reservoir, and estimates of the long-term average discharge at all reservoir locations.

■ Estimating the amount and volume of smaller reservoirs

The global distribution of natural lakes and their surface areas can be described by a power law distribution (Lehner and Döll 2004), and a similar Pareto distribution has been proposed for artificial reservoirs (Downing *et al.* 2006). By fitting such a statistical distribution to the GRanD data (WebPanel 2 and WebFigure 1), we extrapolated the number, total surface area, and volume of smaller reservoirs. Table 1 indicates good overall correspondence between GRanD and the Pareto model in the reservoir size classes 10 km^2 to 10 000 km^2. For the calculation of total global numbers, we combined GRanD data for reservoirs larger than 10 km^2 with the values derived from the Pareto model for smaller reservoirs.

We estimate that there are about 2.8 million impoundments larger than 0.1 ha (0.001 km^2) worldwide, and 16.7 million when including those larger than 0.01 ha (100 m^2; Table 1). The total storage volume of all reservoirs amounts to 8069 km^3 and their combined area covers 305 723 km^2 (excluding regulated natural lakes), equivalent to an increase of Earth's naturally occurring terrestrial water surface by 7.3% (Downing *et al.* 2006).

Previous estimates of the numbers, surface areas, and/or storage capacities of large and small reservoirs differed considerably among published studies (eg St Louis *et al.* 2000; Lehner and Döll 2004; Downing *et al.* 2006; Wisser *et al.* 2010), some indicating a substantially higher surface extent than ours (up to fivefold). Yet by distinguishing between human-made reservoirs and (albeit currently limited to only very large) regulated natural lakes, GRanD enables a more robust analysis for estimating total reservoir area. Thus we believe that previous approximations, by not accounting for such a distinction, may have generated overestimates. Furthermore, our results align reasonably well with those of Downing *et al.* (2006) – which show slightly higher numbers of very small reservoirs – and also agree with the total surface area recorded in the World Register of Dams (~400 000 km^2, including regulated natural lakes; ICOLD 1998–2009). Because the reservoir volume follows a saturating function, the total global storage volume is mostly determined by large reservoirs. This observation fits well with previous studies (Vörösmarty *et al.* 2003), and the results indicate that GRanD captures more than 75% of the total global storage capacity.

Quantifying the global degree of river regulation

The proportion of a river's annual flow that can be withheld by a reservoir or cluster of reservoirs can serve as a first-level approximation of the potential impact on downstream flows. This index, which – following other authors – we term "degree of regulation" (DOR), has in one form or another been a key component of seminal studies on flow regulation (eg Nilsson *et al.* 2005) or has been analyzed in terms of the hydrologically equivalent "change in residence time" or "water aging" (eg Vörösmarty *et al.* 1997). However, these studies were limited in scale and extent – typically providing single values for only the world's largest river basins – because of poor data availability for dams, reservoirs, and global river hydrography. Building on these efforts, we present advanced and spatially detailed calculations of DOR by coupling GRanD with the global HydroSHEDS river network (Lehner *et al.* 2008).

A high DOR value indicates an increased probability that substantial discharge volumes can be stored throughout a given year and released at later times. Both temporal storage and delayed release alter the natural flow regime and, as a result of the increased stagnation and stratification of the stored water, can also affect other characteristics, such as water temperature, dissolved oxygen content, or suspended sediment load. In particular, multi-year reservoirs (DOR > 100%) have the ability to release water in accordance with an artificial, demand-driven regime, often with the explicit goal to supply water in contrast to natural expectations, such as by increasing dry-season flows or eliminating flood peaks. Among the largest 100 reservoirs in GRanD, 27 showed individual DOR ratios above 200%, including the Hoover Dam in the US (284%) and the African Akosombo and Kariba dams (each exceeding 300%). Although smaller DOR ratios may imply less of a general impact, some critical aspects of the flow regime may still be severely altered. For example, China's Three Gorges Dam can store only 4.5% of the total annual flow of the Yangtze River, but its design purpose is to eliminate smaller floods and to reduce extreme events, and it has substantially altered the downstream sediment transport of the Yangtze (Xu and Milliman 2009). Dynesius and Nilsson (1994) used a DOR threshold of 2% – equivalent to the capacity of storing about one week of the total annual flow – to distinguish between free-flowing rivers and the onset of ecological consequences. In the same sense, here we refer to rivers with a DOR ≥2% as "affected" rivers, yet we provide additional results for a suite of higher DOR thresholds in order to support a more differentiated interpretation. For details of our DOR calculations, see WebPanel 3.

Global statistics and maps of the affected river network are provided in Table 2 and Figures 2 and 3. Obviously, higher DOR thresholds lead to smaller absolute extents of affected river reaches. Independently from the threshold, however, the relative impact increases with river size, peaking at large rivers (1000 $m^3 s^{-1}$ to 10 000 $m^3 s^{-1}$; Table

Table 1. Estimation of the global number of reservoirs, representative mean areas per size class, total areas, and reservoir volumes, as compiled in GRanD and as derived from the Pareto distribution model (see WebPanel 2), grouped by reservoir size classes

Reservoir surface area (km^2)		*GRanD*				*Pareto model*			
Min	*Max*	*Number*[a]	*Avg area (km^2)*	*Total area*[b] *(10^3 km^2)*	*Volume (km^3)*	*Number*	*Avg area (km^2)*	*Total area (10^3 km^2)*	*Volume (km^3)*
0.0001	0.001					13 951 674	0.000280	3.9	169.5
0.001	0.01					2 311 673	0.00280	6.5	254.8
0.01	0.1					383 024	0.0280	10.7	383.1
0.1	1	1275	0.48	0.6	35.6	63 464	0.280	17.8	575.9
1	10	3472	3.8	13.2	297.2	10 515	2.80	29.5	865.9
10	100	1683	30.1	50.7	1194.6	1742	28.0	48.8	1301.9
100	1000	348	278.0	96.7	1941.6	289	280.3	80.9	1957.5
1000	10 000	59	2497.3	147.3	2371.4	48	2803.0	134.1	2942.9
10 000	100 000	4	35 973.4	143.9	312.6	8	28 030.3	222.2	4424.6

Total number of reservoirs: 16.7 million	Total reservoir area[b]: 507 102 km^2 *Total added reservoir area*[c]*: 305 723 km^2*	Total storage volume: 8069.3 km^3

Notes: Global totals are calculated as the sum of values from GRanD for reservoirs larger than 10 km^2 and from the Pareto model for reservoirs smaller than 10 km^2. Other values are provided for comparison. [a]A few GRanD reservoirs were not included in the list because of inadequate information on area or volume. [b]The total reservoir area in GRanD includes regulated natural lakes (such as Lakes Victoria, Baikal, and Ontario). [c]The total "added" reservoir area excludes regulated natural lakes (as indicated in GRanD).

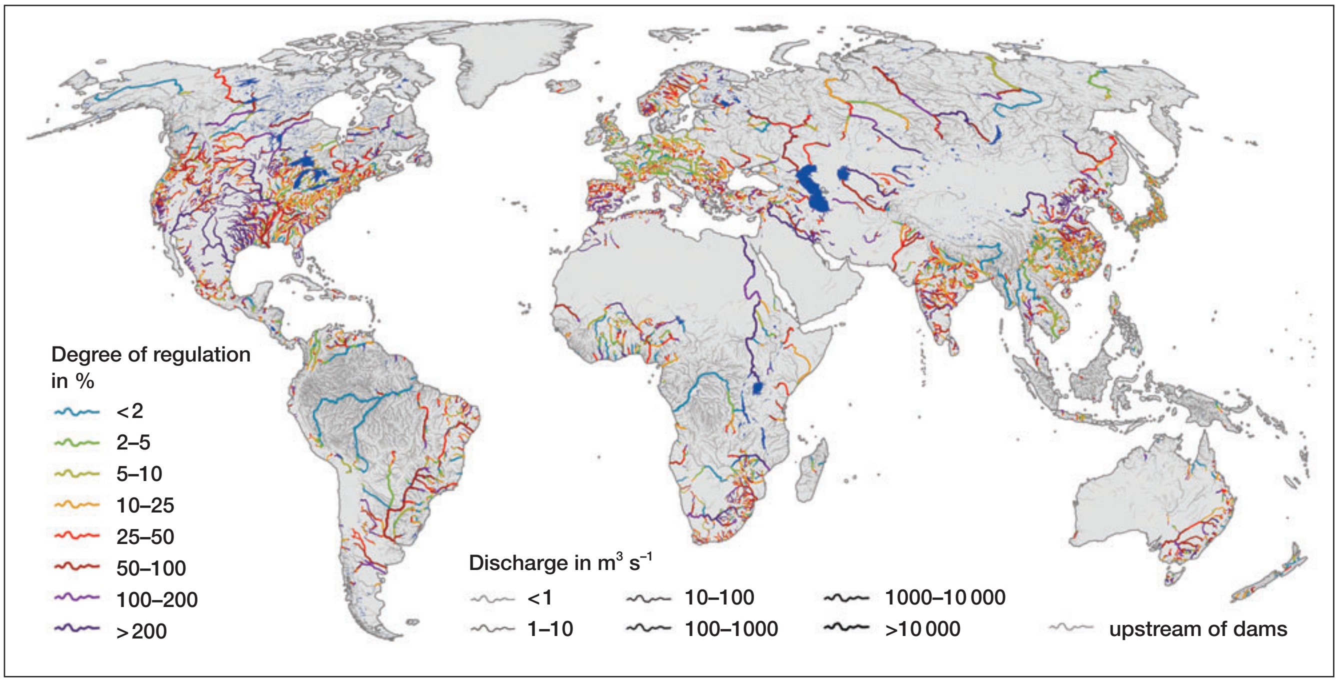

Figure 2. *Affected river reaches downstream of GRanD reservoirs. Different colors show an increasing degree of regulation, whereas line width is proportional to average long-term discharge. Rivers in gray have no large dams upstream.*

2 and Figure 3). Very large rivers show slightly reduced levels again, most likely because massive flows, such as those of the Amazon or Congo rivers, cannot easily be impounded in their entirety. When adopting a DOR threshold of 2%, we find that 575 900 river kilometers, or 7.6% of the world's rivers with average flows exceeding 1 m^3 s^{-1}, are affected by upstream reservoirs. Of these, 84 300 km are large rivers with average flows of more than 1000 m^3 s^{-1}, representing 46.7% of all rivers in this size class globally. Approximately 117 500 km, or 2.3% of small rivers with average flows below 10 m^3 s^{-1}, are affected. In total, 139 200 river kilometers have enough cumulative reservoir capacity in their respective upstream catchment to store more than the entire annual river flow (DOR ≥ 100%; Table 2).

Several basins and countries stand out as being highly affected over large areas (for a regional breakdown of results, see Table 3, WebTable 2, and WebFigures 2–8),

Table 2. Global extent of affected rivers (in kilometers and percentages) downstream of GRanD reservoirs, tabulated by river size and degree of regulation (DOR)

River size (average flow in m^3 s^{-1})	Length of all rivers (in 10^3 km)	Global extent of affected rivers downstream of GRanD reservoirs DOR(%) ≥2	≥5	≥10	≥25	≥50	≥100	≥200	Units
Small	5081.9	117.5	113.7	105.0	85.8	65.0	42.5	24.6	10^3 km
(1–10)		*2.3*	*2.2*	*2.1*	*1.7*	*1.3*	*0.8*	*0.5*	%
Small–medium	1696.6	203.3	181.7	158.0	115.4	78.8	44.8	21.6	10^3 km
(10–100)		*12.0*	*10.7*	*9.3*	*6.8*	*4.6*	*2.6*	*1.3*	%
Medium	603.2	170.8	152.0	133.0	100.0	69.0	36.4	15.8	10^3 km
(100–1000)		*28.3*	*25.2*	*22.0*	*16.6*	*11.4*	*6.0*	*2.6*	%
Large	155.7	73.0	64.2	56.2	43.0	30.3	15.3	7.0	10^3 km
(1000–10 000)		*46.9*	*41.3*	*36.1*	*27.6*	*19.5*	*9.8*	*4.5*	%
Very large	25.0	11.3	10.7	8.5	5.1	4.1	0.2	0.0	10^3 km
(>10 000)		*45.1*	*42.8*	*34.0*	*20.3*	*16.2*	*0.9*	*0.0*	%
Total	**7562.4**	**575.9**	**522.4**	**460.7**	**349.4**	**247.3**	**139.2**	**69.0**	**10^3 km**
		7.6	***6.9***	***6.1***	***4.6***	***3.3***	***1.8***	***0.9***	**%**

Notes: DOR is the cumulative upstream storage in percent of average flow. All length estimates were calculated from the HydroSHEDS river network at 15 arc-second resolution (Lehner *et al.* 2008).

with many impacted tributaries resulting from a multitude of dispersed dams, such as those of the Mississippi–Missouri Basin in North America or in parts of Europe and Asia, including India and China. In other basins, such as the Parana–Paraguay in South America, effects are concentrated to certain sub-basins. Singular dams can have the potential for abrupt but severe alterations in the DOR ratio, and the effects can propagate far downstream on the main-stem river, as is apparent in the Nile, Senegal, or Zambezi basins of Africa. Overall, our results – albeit at much higher spatial resolution – agree with previous findings indicating that reservoirs intercept more than 40% of global river discharge (Vörösmarty *et al*. 2003), and that more than 50% of large river systems are affected by dams (Nilsson *et al*. 2005).

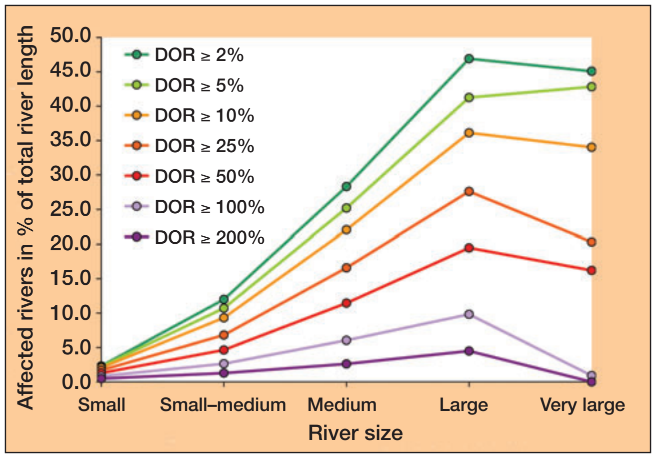

Figure 3. *Percent of affected river length for different DOR thresholds. River size classes are defined in Table 2.*

Uncertainties and sensitivity analysis

The results of our DOR study need careful interpretation to avoid arriving at misleading global generalizations. First, the impacts and consequences of flow regulation may vary for different river size classes. Large rivers are more likely to be of high regional or international importance, including far-reaching ecological and socioeconomic aspects, and strong dependencies between agricultural practices, fisheries, and natural river flows may exist. Yet smaller streams can provide local ecosystem services, serve as ecological refuges, or may represent headwater reaches important for municipal water supply. Second, the DOR ratio is important. For river reaches with high DOR ratios, major implications for the intra- and inter-annual flow regimes are to be expected. Smaller ratios may represent critical alterations as well, but of shorter duration or smaller amplitude. Third, it will largely depend on the individual reservoir operation scheme

Table 3. Number of dams, total storage capacity, and extent of affected rivers (in kilometers and percentages) downstream of GRanD reservoirs for different continents, tabulated by river size and by degree of regulation (DOR)

			Extent of affected rivers with a DOR ≥2%				*Extent of affected rivers (all river sizes combined)*				
			By river size *(avg flow in m^3 s^{-1})*				**By DOR** *(%)*				
Region	*# of dams*	*Total storage capacity (in km^3)*	*1–10*	*10–100*	*100–1000*	*>1000*	*≥2*	*≥10*	*≥50*	*≥100*	*Units*
Africa	726	997.2	21.5	23.6	18.5	11.0	74.6	59.3	34.7	21.9	10^3 km
			2.9	*9.3*	*18.8*	*43.2*	*6.6*	*5.3*	*3.1*	*1.9*	% *
Asia	1906	1624.9	25.7	50.2	46.2	34.2	156.3	119.7	59.7	32.2	10^3 km
			1.6	*9.3*	*25.0*	*54.9*	*6.6*	*5.1*	*2.5*	*1.4*	% *
Australia	253	95.5	4.8	9.5	5.4	0.0	19.6	17.2	9.9	4.6	10^3 km
			2.4	*15.2*	*44.7*	*0.0*	*7.1*	*6.2*	*3.6*	*1.7*	% *
Europe[a]	1424	892.2	22.1	39.9	33.5	8.9	104.4	79.4	38.8	20.8	10^3 km
			3.9	*21.6*	*54.1*	*79.6*	*12.6*	*9.6*	*4.7*	*2.5*	% *
North America	2094	1574.6	36.0	56.2	45.6	16.5	154.3	132.5	73.5	44.8	10^3 km
			5.0	*23.4*	*54.5*	*79.7*	*14.4*	*12.4*	*6.9*	*4.2*	% *
South America[b]	459	1012.8	7.3	23.9	21.7	13.7	66.6	52.7	30.7	14.9	10^3 km
			0.6	*5.8*	*13.4*	*22.4*	*3.5*	*2.8*	*1.6*	*0.8*	% *
Global total	**6862**	**6197.1**	**117.5**	**203.3**	**170.8**	**84.3**	**575.9**	**460.7**	**247.3**	**139.2**	**10^3 km**
			2.3	***12.0***	***28.3***	***46.7***	***7.6***	***6.1***	***3.3***	***1.8***	**% ***
Global ≥0.5 km^3	1122	5689.0	10.1	66.7	130.9	80.2	287.9	253.1	156.5	92.9	10^3 km
			0.2	*3.9*	*21.7*	*44.4*	*3.8*	*3.3*	*2.1*	*1.2*	% *

Notes: The bottom row (Global ≥ 0.5 km^3) reports results derived from only those reservoirs with storage capacities ≥ 0.5 km^3. [a]Including western Russia and the Middle East. [b]Including Central America and the Caribbean. *For the results "by river size", the percent value refers to all rivers of the respective size class in the region; for the results "by DOR", the percent value refers to all rivers of all sizes in the region.

and/or additional effects, such as the level of water abstraction, whether the downstream flows are compromised. Some dams with large potential capacities, such as the Owen Falls Dam across the White Nile downstream of Lake Victoria, are not used to maximize storage but are operated as run-of-the-river hydropower plants; for other dams, the implementation of environmental flow standards may mitigate the indicated effects. Finally, we recognize that ecological effects may vary and that some river habitats may be more threatened than others by a certain level of regulation. Clearly, more research is needed regarding the associated ecological consequences.

There are many small reservoirs that are not included in GRanD. In particular, our finding that the smaller river size classes show lower impact levels (Table 2; Figure 3) may be severely skewed by the omission of small reservoirs, which are typically located on smaller rivers. Also, though they may contribute less to the overall alteration of flow regimes as a result of their limited storage capacities, small dams can still have a profound effect on river fragmentation.

In order to assess the improvement of GRanD over previous datasets and to test the sensitivity of our DOR estimates with respect to smaller reservoirs, we repeated the calculations using only those reservoirs with a storage capacity larger than 0.5 km^3, which have been the focus of previous global dam databases. We found that this limitation reduced the extent of affected rivers by about 50% (DOR ≥2%; Table 3), with the largest differences occurring for small rivers. This result illustrates that smaller reservoirs are responsible for a substantial increase in the spatial extent of affected rivers, despite their relatively small contribution in total global reservoir capacity.

Intrinsically, our model approach is subject to various uncertainties. Beyond technical issues (see WebPanels 1–3), some aspects could not be addressed because of a lack of data, such as the role of dam operation or sediment trapping. Moreover, river deltas are not represented properly by the HydroSHEDS river network and are thus not fully included in the estimates. Finally, our study only accounts for impacts from upstream reservoirs on downstream river reaches; yet, for many additional upstream tributaries, connectivity and species migration routes may be disrupted or impeded either directly by the presence of downstream dams or indirectly by downstream rivers being exposed to altered flow regimes. Overall, and given the nature of most uncertainties and omissions, we believe that our estimates of the extent of affected rivers are therefore conservative.

Discussion and implications

The quality of available data related to dams and reservoirs is critical in global efforts to better understand the threats to, and to ensure the conservation of, freshwater ecosystems and their dependent natural communities (eg Nilsson *et al.* 2005; Döll *et al.* 2009; Vörösmarty *et al.* 2009, 2010). Indeed, previous studies of the impacts of dams and reservoirs on ecology and human society, from local to global scales, have hitherto been restricted, including only a subset of these structures in any analysis. Similar data constraints have limited the degree to which new construction, operation, and decommissioning of dams are informed decisions. In an era of continued dam construction, particularly in economically developing and water-scarce nations, these decisions must rely on the best available data to guarantee the future sustainability of water resources and for the benefit of the people dependent upon them. For example, nearly 30 new dams were under construction in the Shatt al Arab (Euphrates–Tigris) Basin as of 2004, a basin rife with political conflict, poverty, and severe drought (Altinbilek 2004). If the decisions thus far on location, size, and operation of these dams have suffered from misinformation or insufficient data, then the challenges presented to this basin may be further exacerbated. Moreover, given that many regions will be challenged by climate-change-induced alterations in river flow regimes, different ways of managing dams and reservoirs may favor or limit adaptive capacity (Palmer *et al.* 2008).

With the increased recognition of the value of functioning freshwater ecosystems (Naiman *et al.* 2002), the challenge is to adapt traditional approaches of flow management and meet the needs of both ecosystems and people (Arthington *et al.* 2010). Previous data on dams and reservoirs have been successfully applied to global water-resource management efforts in terms of identifying biomes, nations, or basins for finer-scale studies. The next step is to move concertedly toward addressing critical questions regarding (1) the global distribution of impacts at the river reach scale, (2) the relative impacts of individual dams and reservoirs within basins, and (3) the impacts in small- and medium-sized basins.

With its increased spatial accuracy and attribute coverage, GRanD is a highly versatile geodatabase that is available to support new regional or global analyses at unprecedented spatial resolution, sophistication, and reliability. As evidence for its utility, Vörösmarty *et al.* (2010) have incorporated the database as one indicator to derive a first-time spatially explicit global assessment of threats to human water security and river biodiversity. Also, in a related study, Richter *et al.* (2010) have used our layer of affected river reaches to derive a first-time approximation of the number of people that are potentially affected downstream of reservoirs. Their results show that, globally, 472 million people are living in rural areas downstream of large dams in close proximity (<10 km) to impacted rivers (DOR >10%).

GRanD will also benefit decisions regarding non-dam-related water management schemes, by providing a larger context within which these projects operate. For example, regions such as the Upper Danube and Southern Iberia have little remaining uninterrupted free-flowing river distance, resulting in loss of habitat for dependent species. Water management and/or river restoration schemes in these ecoregions may include designs that offer restoration of essential habitat, while alternative irrigation practices and efficiency gains can help in meeting human needs. We advocate that a more holistic "river network mindset" is required in future strategic planning, and that river basin development and management plans use approaches similar to our DOR assessment to inform decisions regarding the distribution of new dams and/or the operation of existing dams. Additional data and novel assessment techniques may reveal the cumulative effects of dams on the entire river system, helping to identify or restore important linkages and avoid critical thresholds. We envision that regional management schemes could also be "optimized" by prioritizing the siting of new dams based on which locations would have the lowest estimated cumulative impacts downstream. Similarly, dams can be identified where changes in release patterns and operation schemes – or technical interventions, such as fish bypass facilities – would be most likely to improve environmental flows and/or ecosystem services.

One of the most important points to be made with regard to GRanD is a call for active contribution in terms of new data input, data updates, and quality control. This database's continuing utility is largely dependent on the accuracy of its content, including current and robust attribute data, which requires consistent input from the people and organizations that have the most detailed and accurate data on dams and reservoirs in their respective region. For example, the possibilities for conducting innovative, multiscale social analyses will grow as GRanD receives demographic data associated with individual dams and reservoirs, such as size and location of the population served, size of population displaced, estimates of downstream livelihood dependence, and other related economic factors. As the list of desired applications expands, so must the data contributed to GRanD.

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WebPanel 1. Development of GRanD

The most comprehensive global dam database – the World Register of Dams – is compiled by the International Commission on Large Dams (ICOLD) and currently lists more than 33 000 records of large dams and their attributes (ICOLD 1998–2009). However, this inventory is not georeferenced, limiting its utility for many applications. Water resource managers typically need to allocate reservoirs to sub-basins, link them to the drainage network, or relate them to population centers and irrigated areas. Biological and geophysical Earth system studies, conservation planning efforts, and restoration projects all require georeferenced data, preferably with extensive attribute information, spanning both local and global scales.

In previous attempts, several researchers and organizations have created their own georeferenced, global and regional datasets of dams and reservoirs, mostly by identifying the largest of them on paper maps and compiling attribute information from various sources, including national archives and the internet. These databases, however, vary widely in their number of records, the quality of attribute data, and their spatial resolution, ranging from coarse coordinates to lumped national or regional assignments. Among them, the most extensive, publicly available global georeferenced compilation contains some 1500 large reservoirs, a very small number as compared with the globally estimated 50 000 large reservoirs. Also, the absence of a high-resolution global river network precluded use of even the best of these datasets in routed hydrologic analyses, because dams and reservoirs could not be linked to detailed river courses.

The development of GRanD primarily aimed at compiling the available reservoir and dam information (WebTable 1); correcting it through extensive cross-validation, error checking, and identification of duplicate records, attribute conflicts, or mismatches; and completing missing information from new sources or statistical approaches (see below). The dams were geospatially referenced and assigned to polygons depicting reservoir outlines at high spatial resolution. Although the main focus was to include all reservoirs with a storage capacity of more than 0.1 km^3, many smaller reservoirs were added if data were available. In instances where natural lakes are regulated by dams, such as Africa's Lake Victoria, only the added storage volume was considered. Finally, some dams were included because of their importance, such as India's Farakka Barrage, which diverts water from the Ganges River, even if they do not create a traditional reservoir. For more details on the development of GRanD, see the Technical Documentation available at www.gwsp.org/85.html and http://sedac.ciesin.columbia.edu/pfs/grand.html.

In the course of constructing GRanD, two equations were derived and applied in order to complete missing reservoir volumes:

$$V = 0.678\,(A \cdot h)^{0.9229} \quad \text{(Eq 1)} \qquad V = 30.684\,A^{0.9578} \quad \text{(Eq 2)}$$

where V = reservoir volume in 10^6 m^3; A = reservoir area in km^2; and h = dam height in m. Equation 1 was used to estimate missing reservoir volumes if both area and dam height were available (r^2 = 0.92); Equation 2 was used if only the reservoir area was available (r^2 = 0.80). Both equations were determined by a statistical regression analysis of 5824 reservoirs included in GRanD that were selected based on the completeness and reliability of their data (for details, see GRanD Technical Documentation).

WebPanel 2. Estimating the global distribution of reservoirs with a Pareto model

The Pareto distribution can be expressed in the power law form of $N = \alpha A^{-\beta}$, where N is the number of reservoirs with a surface area larger than A, and α and β are the parameters to be fitted. In order to apply this approach to GRanD, we first excluded reservoirs smaller than 10 km^2 because we consider these increasingly incomplete in the records of GRanD. We then derived the (uncorrected) global reservoir distribution as:

$$N = 13964\, A^{-0.7807} \qquad \text{(Eq 3)}$$

where N is the number of reservoirs larger than A, and A is the reservoir surface area in km^2 (WebFigure 1). Note that while $r^2 = 0.994$, the gradient of the trendline strongly depends on the underlying data and assumes true completeness of the records for reservoirs equal or larger than 10 km^2, which is not warranted in GRanD. Also, the construction of reservoirs larger than 1000 km^2 seems increasingly case-specific and aligns less closely with the derived statistical distribution.

Following the approach by Downing *et al*. (2006), the value for α in Equation 3 can be corrected as follows:

$$\alpha = \frac{N_G}{(A_{Gmin}^{-\beta} - A_{Gmax}^{-\beta})} \qquad \text{(Eq 4)}$$

where N_G is the total number of reservoirs in GRanD in the size range 10–1000 km^2 ($N_G = 2031$); A_{Gmin} and A_{Gmax} are 10 and 1000 [km^2], respectively; and $\beta = 0.7807$. Through this correction, the global reservoir distribution is:

$$N = 12604\, A^{-0.7807} \qquad \text{(Eq 5)}$$

The number of reservoirs in a size range (as shown in Table 1) is:

$$N_{A_{min}-A_{max}} = \alpha \cdot (A_{min}^{-\beta} - A_{max}^{-\beta}) \qquad \text{(Eq 6)}$$

where A_{min} and A_{max} are the lower and upper area limits of the size class to be calculated, and α is the corrected α of Equation 4 (ie α = 12 604).

The average area in a size range is:

$$\overline{A}_{A_{min}-A_{max}} = \beta \cdot \frac{-A_{max}\, A_{min}^{-\beta} + A_{max}^{-\beta} A_{min}}{(\beta - 1)\,(A_{max}^{-\beta} - A_{min}^{-\beta})} \qquad \text{(Eq 7)}$$

In Table 1, the total area for the Pareto model is calculated by multiplying the number of reservoirs with the mean area per size class. The total volume is then calculated by applying Equation 2 (see WebPanel 1) to the mean area per size class. Note that this approach assumes a linear relationship between reservoir area and volume; because the exponent in Equation 2 is close to 1, the error has been tested to be less than 1%.

WebPanel 3. Calculation of DOR values

Using standard geographic information system (GIS) functionality, we accumulated the storage capacity of all recorded GRanD reservoirs along the HydroSHEDS river network, providing a "total upstream storage capacity" for every river reach. At the applied HydroSHEDS pixel resolution of 15 arc-seconds (~500 m), the perennial stream network of rivers larger than 1 m^3 s^{-1} consists of about 3.5 million reaches with an average reach length of 2.2 km. HydroSHEDS also includes estimates of long-term (1961–1990) average annual river flows, based on coarse-scale runoff estimates from the global water balance model WaterGAP (Alcamo *et al*. 2003; Döll *et al*. 2003). We thus could calculate DOR ratios for all river reaches by comparing the total accumulated upstream storage capacity with the average flow at every reach location. Finally, we computed the total lengths of affected river reaches, and we grouped the derived results by river sizes from small to very large and by DOR ratios from low to high (Figure 3; Tables 2 and 3; WebTable 2).

Like with all model approaches, our study results are limited by uncertainties, including errors in the reported storage capacities of GRanD; limited accuracy of the assigned dam coordinates; errors in the drainage network of HydroSHEDS; and uncertainties in the discharge estimates, which are ultimately based on a coarse-scale global water balance model. Given that the HydroSHEDS river network is derived from a digital elevation model, its accuracy is influenced by pixel resolution. We evaluated the quality of the length estimates by comparing them to selected river courses that were digitized at high precision from remote-sensing imagery (including the 10 longest rivers globally). This comparison indicated average errors of less than 5% in our length calculations.

WebTable 1. Institutions that participated in the development of GRanD (in alphabetical order), their provided datasets, focus of contribution, and number of provided records

Institution	*Provided data and focus of contribution*	*# of independent data records*[a]
European Environment Agency, Denmark	Provided point and attribute data for Europe[b]	3793 (Europe)
Food and Agriculture Organization of the United Nations (FAO)	Provided point and attribute data for Africa (AQUASTAT[c])	1138 (Africa)
McGill University, Canada	Provided GLWD[d]; updated/improved data for Australia[e] and globally; final global data consolidation of GRanD	1226 (GLWD); 846 (Australia)
The Nature Conservancy (TNC), US	Updated/improved data for South America	149 (South America)
University of Frankfurt, Germany	Coauthor of GLWD[d]; updated/improved data for China	568 (China)
University of Greifswald, Germany	Provided global point and attribute data; updated/improved data for Europe	8157 (global, excluding the US, China, Africa); 4230 (Europe)
University of Kassel, Germany	Coauthor of GLWD[d]	–
University of New Hampshire, US	Provided global point and attribute data; updated/improved data for North America (including NID[f])	1897 (US); 236 (Canada); 226 (Mexico)
Umeå University, Sweden	Provided global point and attribute data	5575 (global, excluding North America, Europe, Russia)
University of Yamanashi, Japan	Provided global point, polygon, and attribute data; updated/improved data for Japan	15 073 points[g], 4648 polygons (global); 560 (Japan)
World Wildlife Fund (WWF), US	Coauthor of GLWD[d]; updated/improved data for Asia	215 (Asia)

Notes: These collections, in turn, used underlying information from a much wider range of sources, including a variety of regional and national inventories and gazetteers, ICOLD's World Register of Dams (ICOLD 1998–2009), and various publications, monographs, and maps. [a]While datasets have been compiled independently by research groups, many records are based on similar or the same original sources and may thus contain duplicates. [b]The European Environment Agency (EEA) is in the process of systematically georeferencing dams in its working area. For the compilation of GRanD, their draft version of 2007 was used; since then, ~5000 large dams have been located in Europe and are publicly available as components of EEA's river and catchment GIS (ECRINS). [c]AQUASTAT georeferenced database on African dams, version of 2007; FAO (2010). [d]Global Lakes and Wetland Database; Lehner and Döll (2004). [e]Original data provided by Commonwealth of Australia (Geoscience Australia 2004). [f]US National Inventory of Dams (NID; Graf 1999). [g]Mostly compiled from other sources and national databases, including many small dams (eg ~8000 dams in the US from NID[f]).

WebTable 2. Number of dams, total storage capacity, and extent of affected rivers (in kilometers and percentages) downstream of GRanD reservoirs for selected countries and river basins, tabulated by river size and by degree of regulation (DOR)

Region	# of dams	Total storage capacity (in km^3)	*Extent of affected rivers with a DOR ≥2%* – **By river size** *(avg flow in $m^3 s^{-1}$)*				*Extent of affected rivers (all river sizes combined)* – **By DOR** *(%)*				Units
			1–10	*10–100*	*100–1000*	*>1000*	**≥2**	*>10*	*>50*	*>100*	
US	1906	767.5	35.1	52.5	31.8	8.8	**128.2**	110.6	63.0	39.3	10^3 km
			10.3	46.3	81.9	78.1	**25.5**	22.0	12.5	7.8	%*
China	770	451.0	13.9	22.5	17.9	10.5	**64.8**	48.5	25.1	14.6	10^3 km
			4.4	20.5	46.1	78.9	**13.6**	10.2	5.3	3.1	%*
India	320	262.2	4.4	13.1	11.4	4.0	**33.0**	28.1	11.5	4.9	10^3 km
			2.8	20.7	53.1	62.0	**13.1**	11.2	4.6	1.9	%*
Canada	228	860.7	1.7	5.4	13.5	7.4	**28.0**	23.9	12.8	7.9	10^3 km
			0.5	4.2	30.4	81.7	**5.0**	4.2	2.3	1.4	%*
Russia	50	811.8	0.5	1.1	6.4	17.3	**25.3**	19.3	12.2	5.9	10^3 km
			0.1	0.5	7.7	58.2	**2.5**	1.9	1.2	0.6	%*
Brazil	179	530.3	2.3	6.5	8.0	7.5	**24.3**	19.5	9.5	2.8	10^3 km
			0.4	3.4	9.7	22.4	**2.7**	2.2	1.1	0.3	%*
Australia	188	78.6	4.5	9.1	4.6	0.0	**18.2**	16.2	9.6	4.5	10^3 km
			2.6	17.1	44.4	0.0	**7.7**	6.8	4.1	1.9	%*
South Africa	271	33.1	8.1	6.1	1.9	0.0	**16.1**	14.1	8.7	5.5	10^3 km
			36.7	68.0	77.3	0.0	**48.1**	42.3	26.1	16.4	%*
Japan	543	19.6	4.7	5.4	1.1	0.0	**11.2**	6.3	0.9	0.1	10^3 km
			14.0	57.0	94.7	0.0	**25.3**	14.2	2.0	0.3	%*
Spain	254	58.0	4.5	4.4	1.4	0.0	**10.4**	10.1	6.5	4.5	10^3 km
			24.5	76.6	90.5	0.0	**40.3**	39.2	25.1	17.4	%*
Mississippi	707	329.9	14.0	22.1	14.4	6.0	**56.5**	49.7	28.8	18.0	10^3 km
			11.6	49.5	91.1	96.1	**30.2**	26.6	15.4	9.6	%*
Yangtze	371	192.6	5.9	10.0	8.1	6.0	**29.9**	19.9	7.9	3.2	10^3 km
			5.0	23.8	49.7	81.6	**16.4**	10.9	4.3	1.7	%*
Danube	184	21.9	3.1	5.0	4.0	2.5	**14.6**	8.2	2.3	0.9	10^3 km
			8.2	37.7	68.4	94.3	**24.7**	13.9	3.9	1.5	%*
Parana	71	314.9	0.2	1.9	4.5	5.8	**12.4**	9.9	6.5	1.7	10^3 km
			0.2	4.3	26.4	97.2	**6.6**	5.2	3.4	0.9	%*
Ganges	81	81.7	1.1	2.8	3.7	2.3	**9.9**	7.5	1.7	0.7	10^3 km
			1.1	6.6	22.8	34.2	**5.9**	4.4	1.0	0.4	%*
Murray-Darling	55	23.4	1.3	5.0	3.6	0.0	**9.8**	9.1	6.3	2.4	10^3 km
			7.8	68.0	95.2	0.0	**36.2**	33.6	23.3	8.9	%*
Euphrates–Tigris	33	228.8	0.4	1.7	5.2	0.1	**7.4**	7.0	5.8	4.2	10^3 km
			2.2	27.2	87.7	96.3	**25.3**	23.8	19.9	14.3	%*
Nile	9	376.5	0.0	0.2	0.7	6.2	**7.2**	6.2	5.7	5.6	10^3 km
			0.0	0.7	11.1	91.9	**7.6**	6.6	6.0	5.9	%*
Zambezi	59	258.0	1.5	1.9	1.0	1.1	**5.6**	3.5	1.8	1.3	10^3 km
			3.2	12.2	16.8	39.3	**7.7**	4.8	2.5	1.8	%*
Volga	17	195.5	0.1	0.4	1.3	3.6	**5.4**	4.2	2.4	0.1	10^3 km
			0.2	2.1	18.5	88.9	**6.2**	4.8	2.7	0.1	%*
Indus	25	49.3	0.1	0.4	2.6	1.9	**5.0**	4.3	1.9	0.2	10^3 km
			0.4	4.4	44.5	92.7	**12.6**	11.0	4.7	0.6	%*
Rio Grande	35	30.4	1.0	2.9	0.9	0.0	**4.8**	4.7	4.6	4.5	10^3 km
			15.9	84.0	93.3	0.0	**45.3**	44.8	43.9	42.7	%*

Notes: *For the results "by river size", the percent value refers to all rivers of the respective size class in the region; for the results "by DOR", the percent value refers to all rivers of all size classes in the region.

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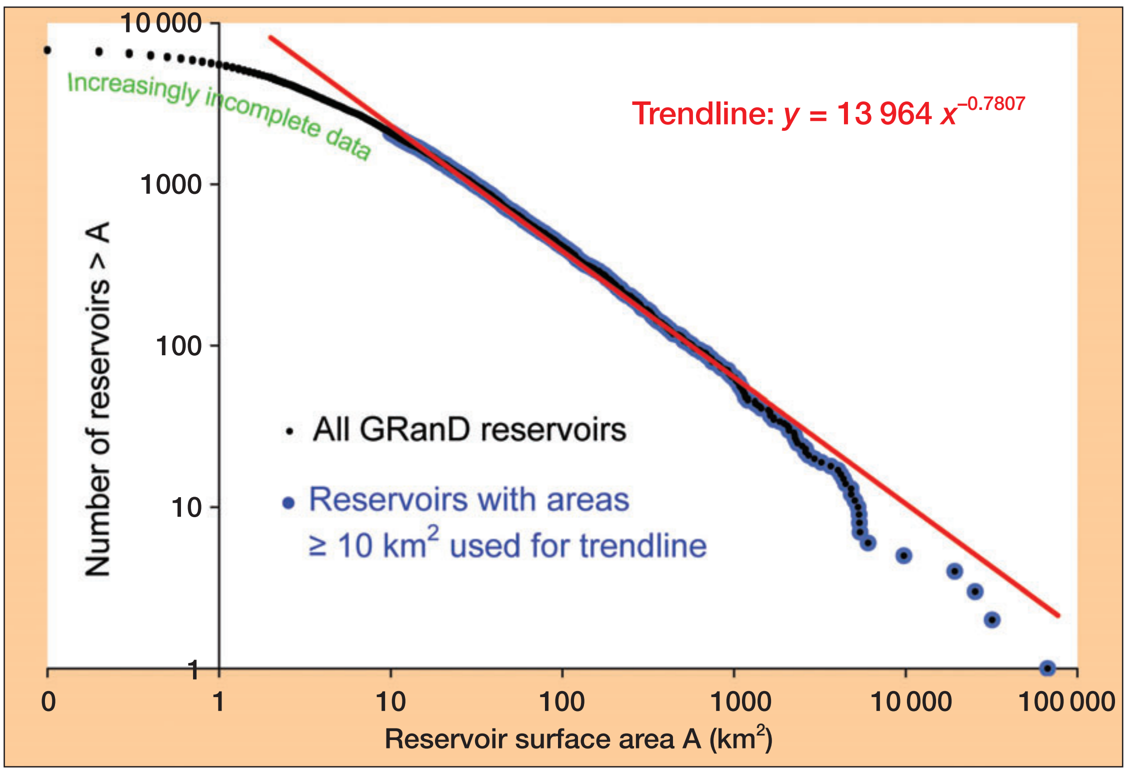
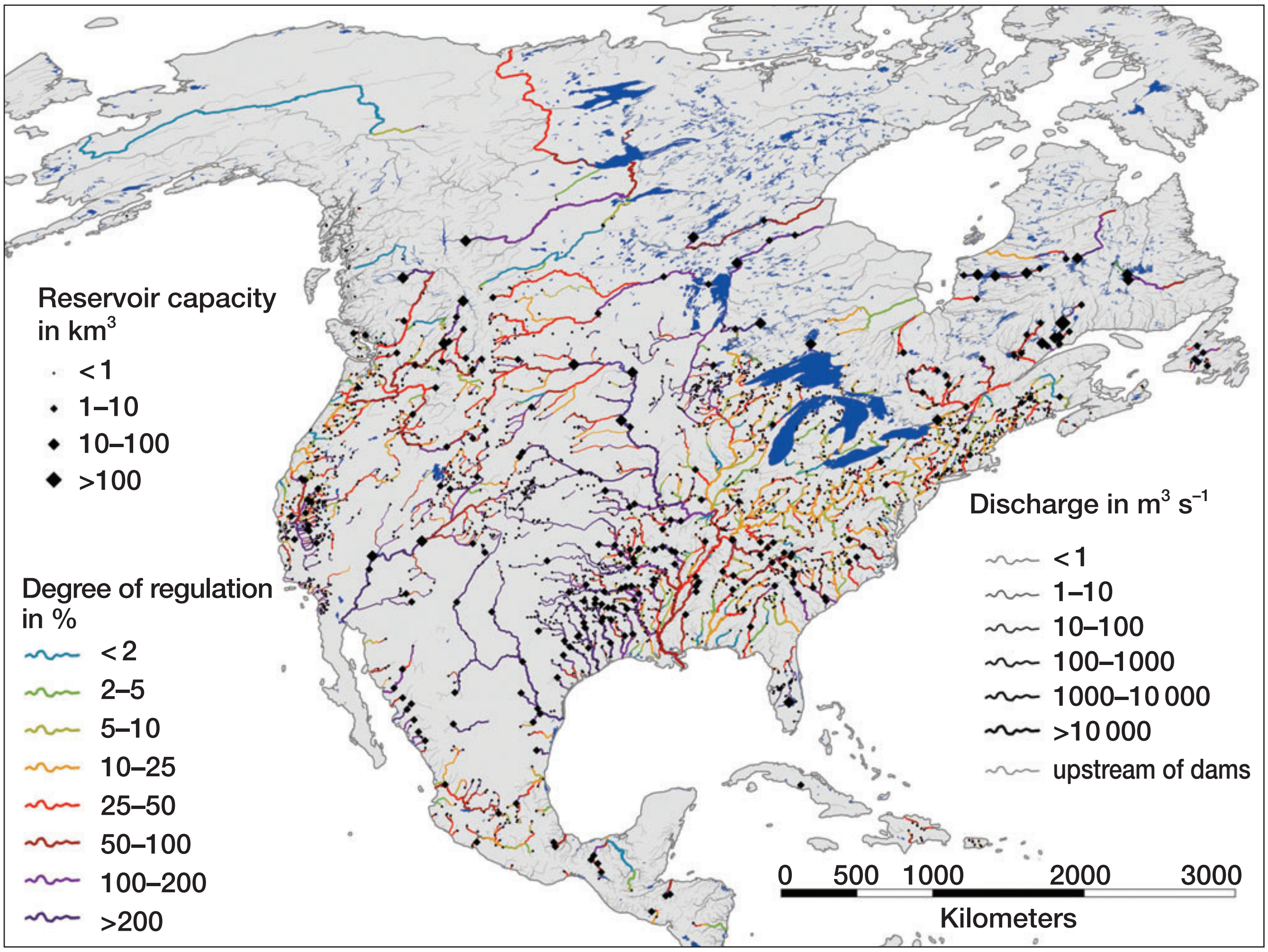
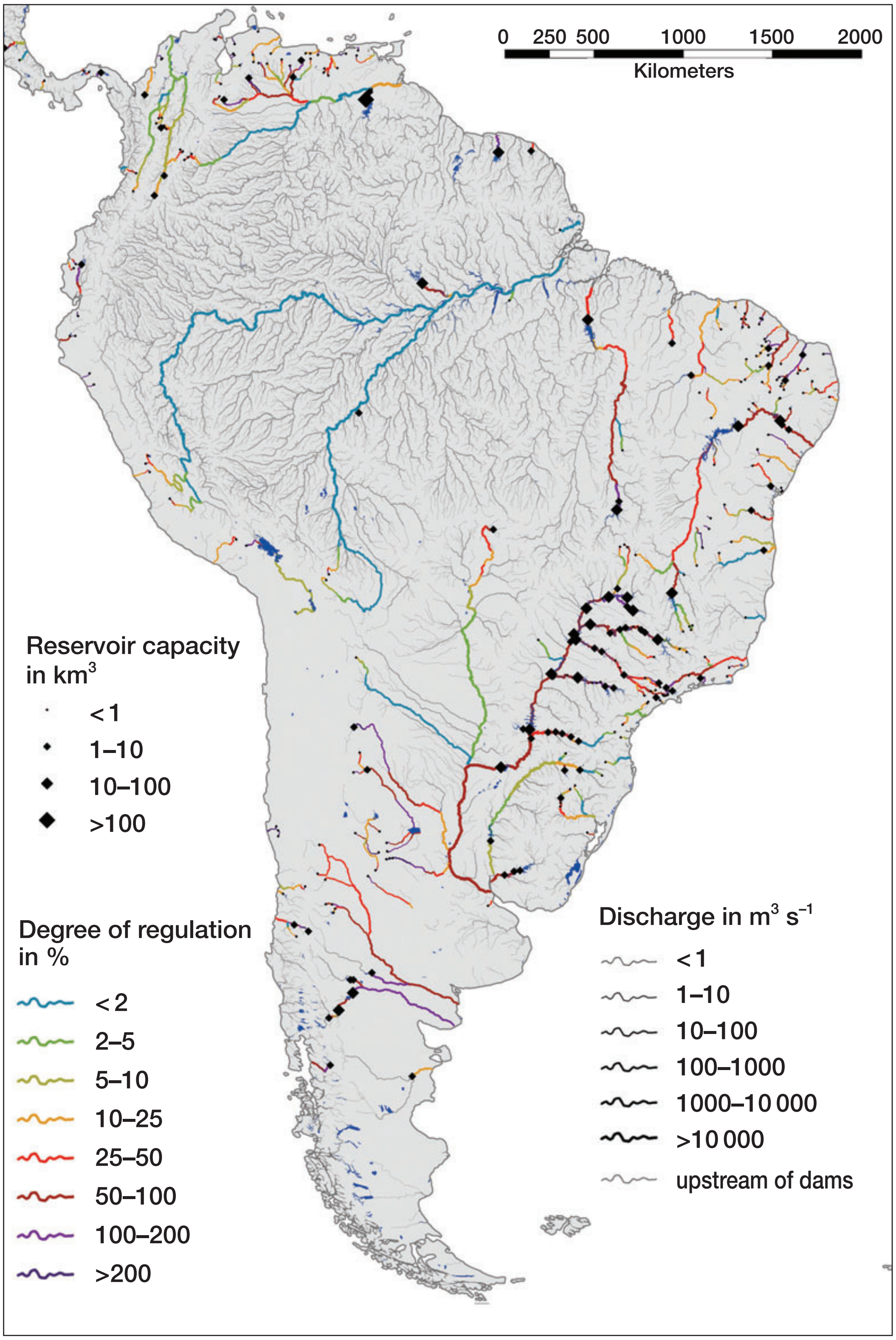


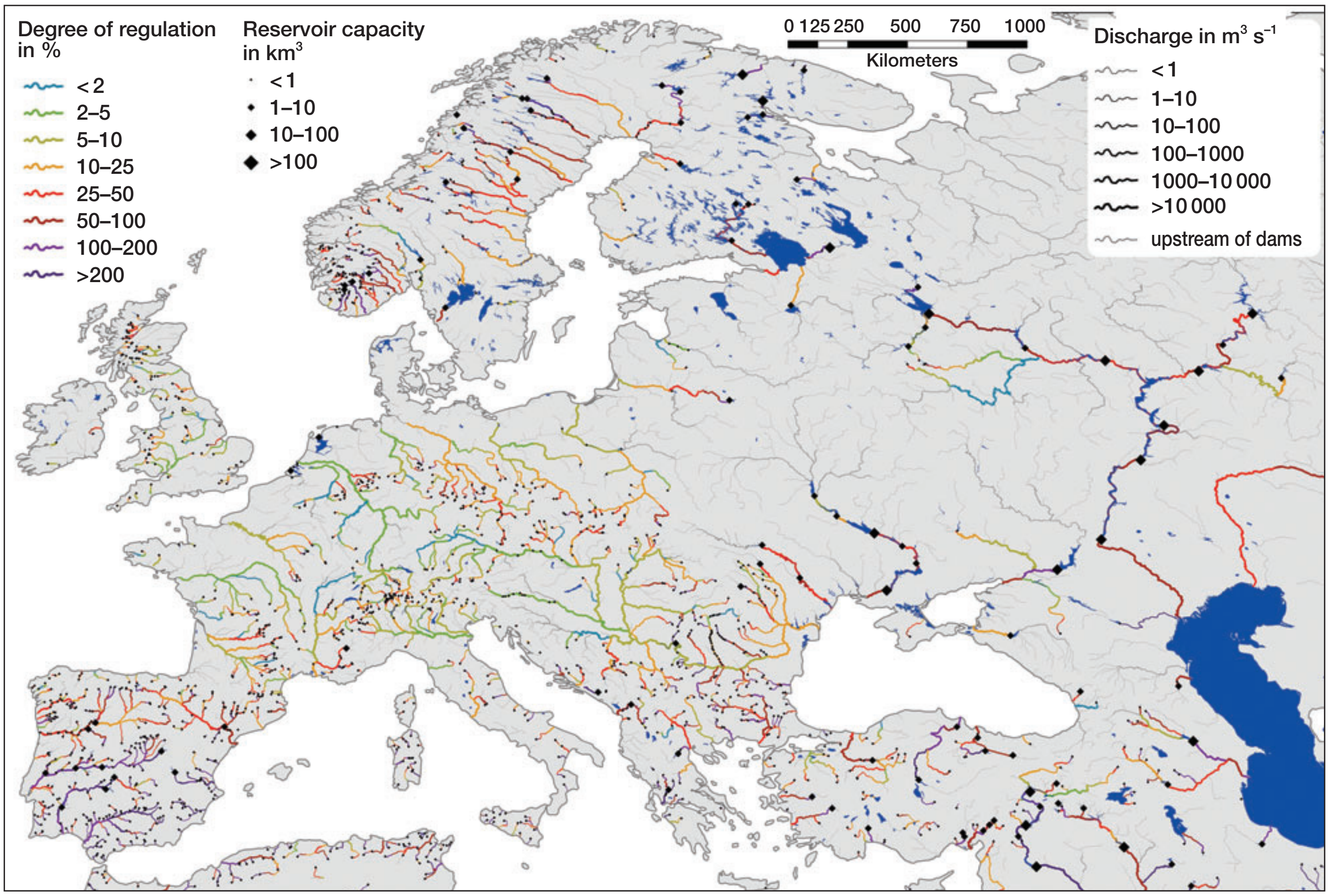
WebFigure 1. *Number of reservoirs (y axis) exceeding increasing surface areas (x axis), based on GRanD. Assuming that the reservoirs larger than 10 km^2 surface area are complete records, a trendline can be fitted and extrapolated following a Pareto distribution in order to estimate smaller reservoirs that are not contained in the database.*



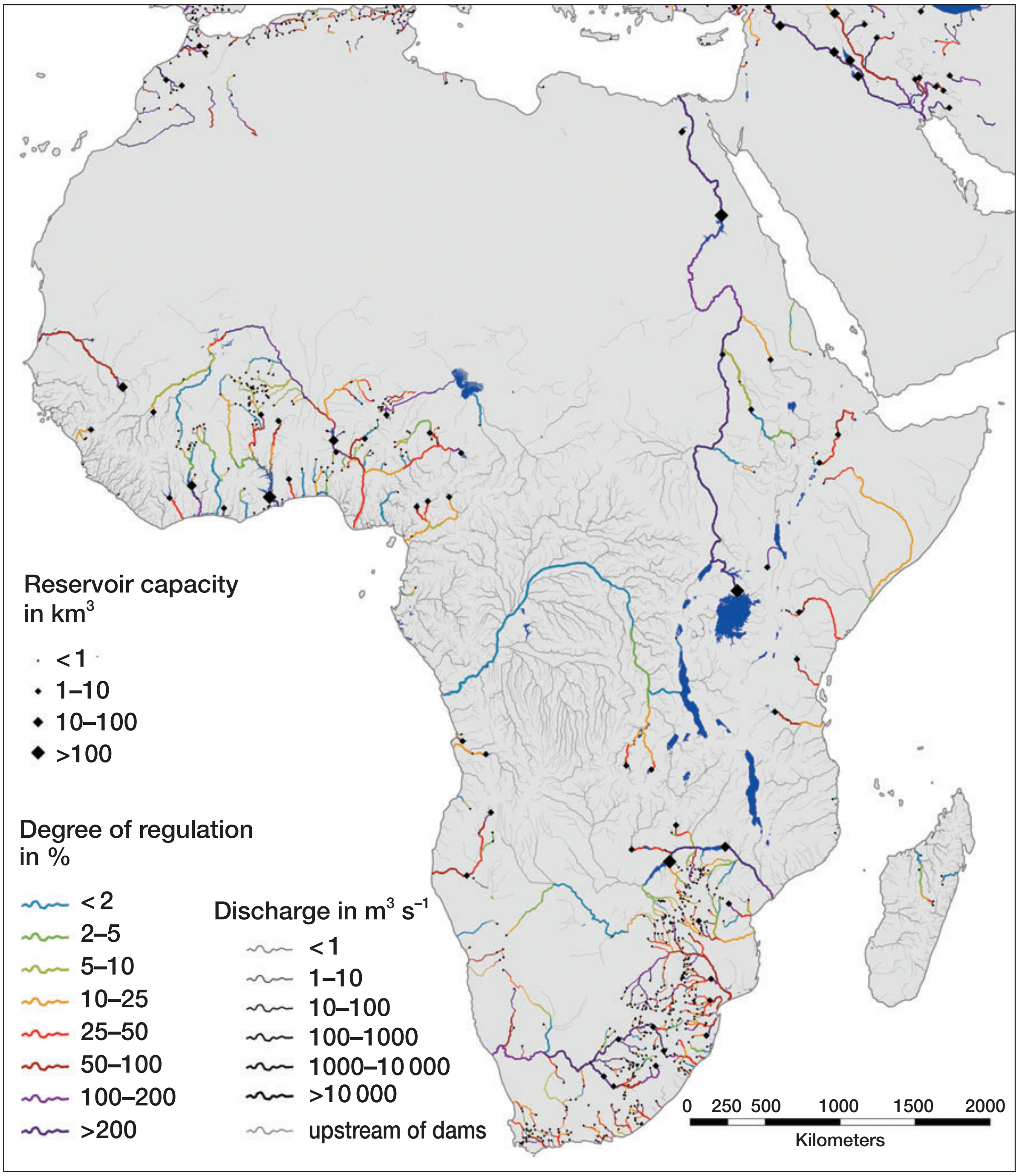
WebFigure 2. *Affected river reaches downstream of GRanD reservoirs in North America.*



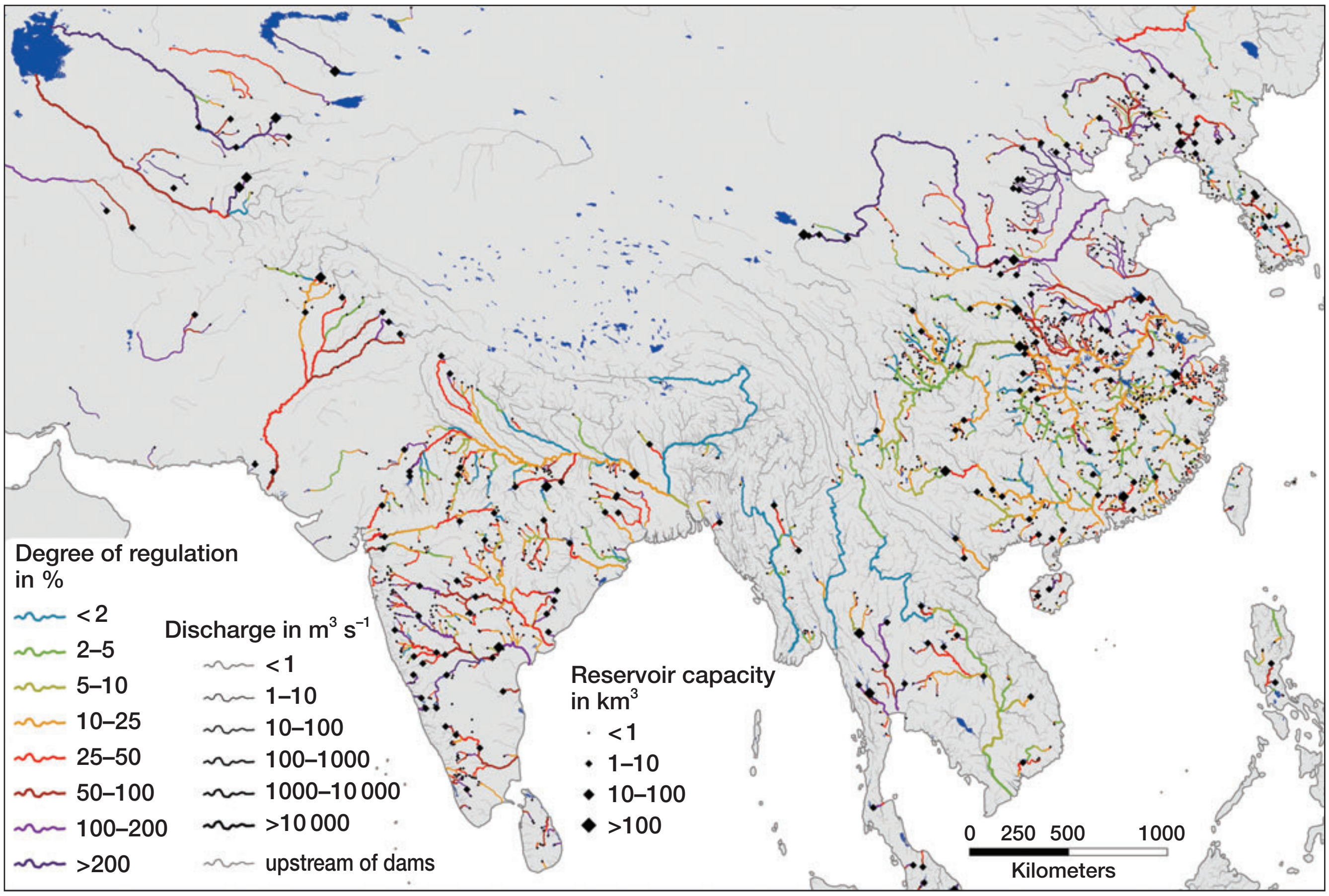
WebFigure 3. *Affected river reaches downstream of GRanD reservoirs in South America.*



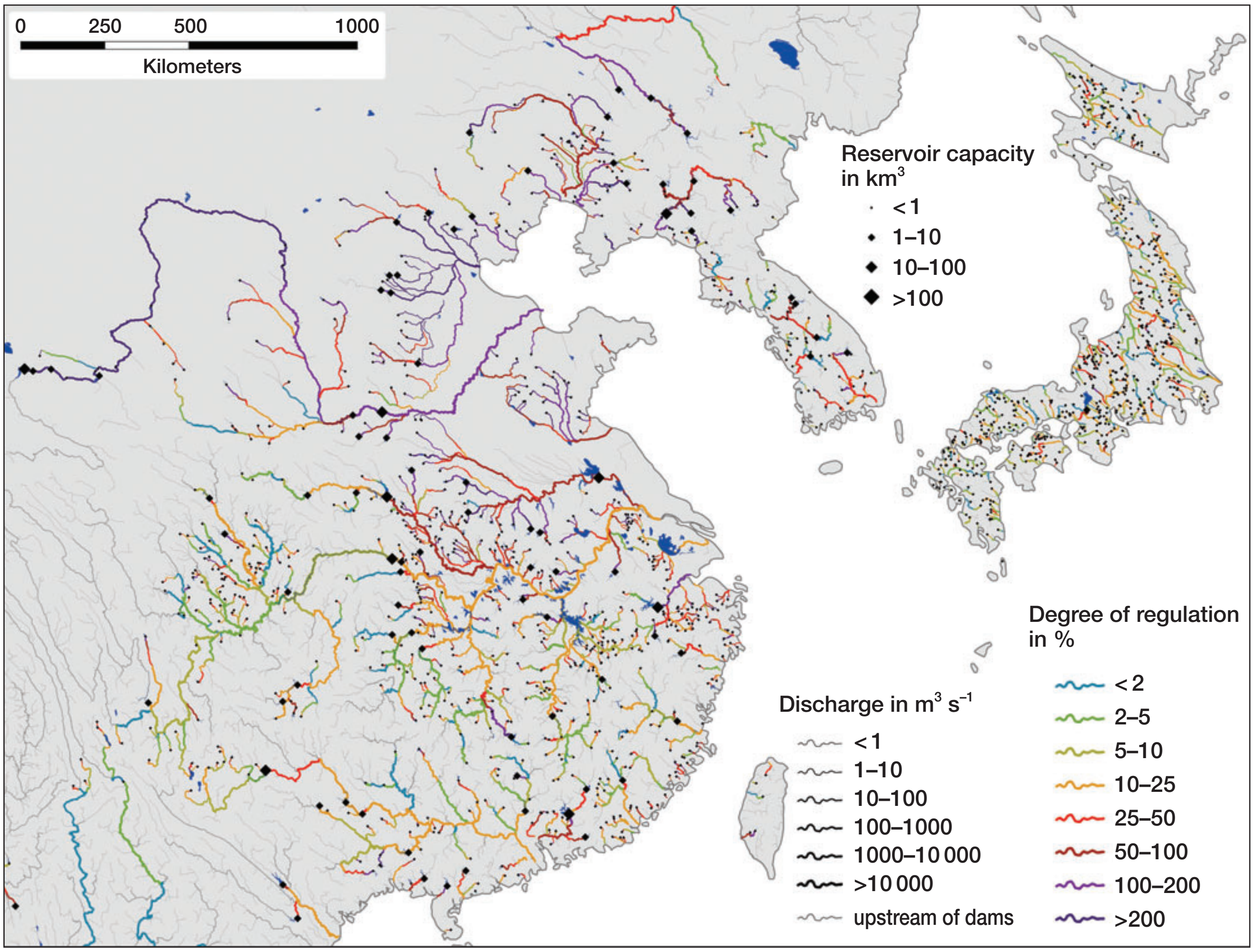
WebFigure 4. *Affected river reaches downstream of GRanD reservoirs in Europe.*



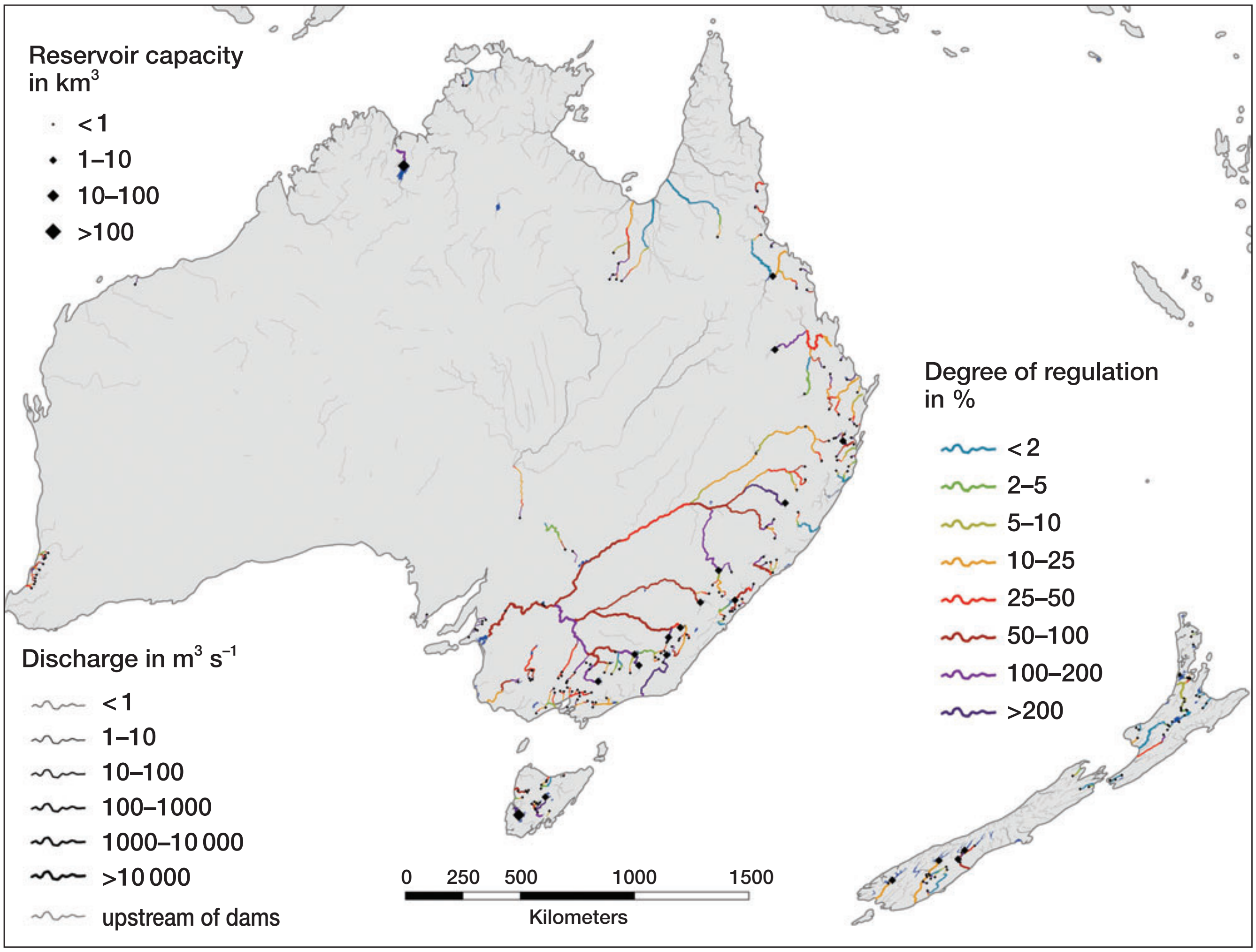
WebFigure 5. *Affected river reaches downstream of GRanD reservoirs in Africa.*



WebFigure 6. *Affected river reaches downstream of GRanD reservoirs in southern Asia.*



WebFigure 7. *Affected river reaches downstream of GRanD reservoirs in Southeast Asia.*



WebFigure 8. *Affected river reaches downstream of GRanD reservoirs in Australia and New Zealand.*