Supplementary Materials for

**Reconciling Dam Development with River Conservation**

M.L. Thieme, D. Tickner, G. Grill, J.P. Carvallo, M. Goichot, J. Hartmann, J. Higgins, B. Lehner, M. Mulligan, C. Nilsson, K. Tockner, C. Zarfl, J. Opperman

Correspondence to: Michele Thieme, 1250 24th Street, NW, Washington, DC 20037 [michele.thieme@wwfus.org](mailto:michele.thieme@wwfus.org)

**This PDF file includes:**

Materials and Methods

Supplementary Tables S1, S2 and S3

**Materials and Methods**

Overview

The global extent of free-flowing rivers has been diminished rapidly in the past due to infrastructure development such as hydropower dams. Here, we compare today’s extent and distribution of free-flowing rivers([Grill et al., 2019](#_ENREF_14)) with a future scenario in which a set of under-construction and proposed (under-consideration) dams was used([Zarfl et al., 2015](#_ENREF_41)).

Mapping the world’s free-flowing rivers

The mapping of the world’s free-flowing rivers (FFRs) is based on an assessment of the connectivity status of 12 million kilometers of rivers globally, identifying those that remain free-flowing in their entire length. Grill et al.([Grill et al., 2019](#_ENREF_14)) used five pressure factors to assess the connectivity status: (a) river fragmentation; (b) flow regulation; (c) sediment trapping; (d) water consumption (surface or groundwater abstractions); and (e) infrastructure development in riparian and floodplain areas. They quantified these factors through six proxy indicators using data from available global remote sensing products, other data compilations, or numerical model outputs such as discharge simulations.

A multi-criteria weighting model was used to combine the six pressure indicators into the Connectivity Status Index (CSI) and a classification algorithm was applied to identify rivers that maintain a free-flowing status over their entire length. Non-free-flowing rivers can show a mix of stretches with ‘good connectivity status’ and stretches that are impacted.

For a detailed description of the materials and methods used to assess the extent and distribution of FFRs, please see Grill et al.([Grill et al., 2019](#_ENREF_14)).

Definition and calculation of scenarios

For this paper, we used a simple scenario assessment methodology to estimate the changes to the connectivity and FFR status of the global river system in response to potential future construction of hydropower dams.

We calculated two scenarios and the difference between the two:

(a) **"Current scenario"**: For today’s situation, we used infrastructure information based on roads, urbanization, and existing dams. For the dam data we included 6,850 large dams as compiled in the Global Reservoir and Dam (GRanD) database, after removing a small number of dams with undefined status, and 13,196 medium to smaller dams from the GlObal geOreferenced Database of Dams (GOODD). These global dam datasets (available at [www.globaldamwatch.org](http://www.globaldamwatch.org)) include both hydropower dams as well as dams of other purposes.

(b) **"Future scenario":** For the situation representing the future, we used the same infrastructure information as above and added a set of hydropower dams that are under-construction or proposed([Zarfl et al., 2015](#_ENREF_41)).

(c) **"Difference between current and future scenario":** Using the results from the two scenarios, we analyzed the number and length of free-flowing rivers worldwide by continent and by length category and calculated the difference between the two sets of results (Table S1 and S2). Furthermore, we extracted a geographical dataset of rivers that would lose their free-flowing status due to future hydropower construction (Figure 1; Table S3).

Potential to maintain FFRs free from development

To highlight the feasibility of positively influencing the fate of the global river system through avoiding impacts on FFRs, we conducted an analysis to estimate the installed capacity of proposed hydropower projects that would have to be replaced by other energy sources. For this, we considered only proposed dam projects as potentially avoidable, and their fate to be conducive to policy changes. Therefore, we considered under-construction dams as built, and grouped them together with existing dams. We then calculated the sum of installed capacity of proposed hydropower projects on FFRs by river length category.

To maintain the status of all of today's FFRs, approximately 212 GW of installed capacity would have to be replaced by alternative sources. This represents almost 99 GW of hydropower development that are proposed on shorter rivers (<500 km), 39 GW that are proposed on long (500-1000 km) and 75 GW that are proposed on very long (>1000 km) rivers, such as the Irrawaddy, Congo, Salween and the Amazon.

**Table S1.** Number of free-flowing rivers by length category and continent for the current and future scenario, and difference between the two scenarios (FF = free-flowing).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Current scenario |  |  |  |  |  |  |  |  |  |
|  | 10-100 km | | 100-500 km | | 500-1000 km | | > 1000 km | | Grand Total |
|  | FF | Not FF | FF | Not FF | FF | Not FF | FF | Not FF |  |
| North America | 46,506 | 1,672 | 2,326 | 724 | 43 | 83 | 11 | 33 | 51,398 |
| South America | 78,556 | 1,234 | 2,410 | 414 | 95 | 50 | 23 | 22 | 82,804 |
| Europe | 25,882 | 1,639 | 1,343 | 699 | 33 | 66 | 3 | 22 | 29,687 |
| Africa | 34,402 | 440 | 2,663 | 369 | 129 | 51 | 27 | 31 | 38,112 |
| Asia | 68,472 | 4,676 | 3,246 | 958 | 113 | 90 | 23 | 46 | 77,624 |
| Australia | 26,889 | 273 | 1,045 | 117 | 40 | 20 | 3 | 2 | 28,389 |
| Grand Total | 280,707 | 9,934 | 13,033 | 3,281 | 453 | 360 | 90 | 156 | 308,014 |
| **Percent of length category** | **96.6** | **3.4** | **79.9** | **20.1** | **55.7** | **44.3** | **36.6** | **63.4** |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| Future scenario |  |  |  |  |  |  |  |  |  |
|  | 10-100 km | | 100-500 km | | 500-1000 km | | > 1000 km | | Grand Total |
|  | FF | Not FF | FF | Not FF | FF | Not FF | FF | Not FF |  |
| North America | 46,490 | 1,688 | 2,308 | 742 | 43 | 83 | 10 | 34 | 51,398 |
| South America | 78,040 | 1,750 | 2,140 | 684 | 63 | 82 | 9 | 36 | 82,804 |
| Europe | 25,593 | 1,928 | 1,289 | 753 | 33 | 66 | 3 | 22 | 29,687 |
| Africa | 34,346 | 496 | 2,578 | 454 | 112 | 68 | 16 | 42 | 38,112 |
| Asia | 68,172 | 4,976 | 3,139 | 1,065 | 100 | 103 | 18 | 51 | 77,624 |
| Australia | 26,877 | 285 | 1,037 | 125 | 38 | 22 | 3 | 2 | 28,389 |
| Grand Total | 279,518 | 11,123 | 12,491 | 3,823 | 389 | 424 | 59 | 187 | 308,014 |
| **Percent of length category** | **96.2** | **3.8** | **76.6** | **23.4** | **47.8** | **52.2** | **24.0** | **76.0** |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| Difference |  |  |  |  |  |  |  |  |  |
|  | 10-100 km | | 100-500 km | | 500-1000 km | | > 1000 km | |  |
|  | FF | Not FF | FF | Not FF | FF | Not FF | FF | Not FF |  |
| North America | -16 | 16 | -18 | 18 | 0 | 0 | -1 | 1 |  |
| South America | -516 | 516 | -270 | 270 | -32 | 32 | -14 | 14 |  |
| Europe | -289 | 289 | -54 | 54 | 0 | 0 | 0 | 0 |  |
| Africa | -56 | 56 | -85 | 85 | -17 | 17 | -11 | 11 |  |
| Asia | -300 | 300 | -107 | 107 | -13 | 13 | -5 | 5 |  |
| Australia | -12 | 12 | -8 | 8 | -2 | 2 | 0 | 0 |  |
| Grand Total | -1,189 | 1,189 | -542 | 542 | -64 | 64 | -31 | 31 |  |
| **Percent of length category** | **-0.4** | **0.4** | **-3.3** | **3.3** | **-7.9** | **7.9** | **-12.6** | **12.6** |  |
|  |  |  |  |  |  |  |  |  |  |

**Table S2:** Length (thousand km) of free-flowing rivers by length category and continent for the current and future scenario, and difference between the two scenarios (FF = free-flowing).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Current scenario** | |  |  |  |  |  |  |  |  |
|  | 10-100 km | | 100-500 km | | 500-1000 km | | > 1000 km | | Grand Total |
|  | FF | Not FF | FF | Not FF | FF | Not FF | FF | Not FF |  |
| North America | 1,364.2 | 726.0 | 377.1 | 145.4 | 28.9 | 55.8 | 14.3 | 62.0 | 2,120.2 |
| South America | 1,837.7 | 47.6 | 413.8 | 86.1 | 61.8 | 34.4 | 40.2 | 42.8 | 2,564.4 |
| Europe | 809.0 | 74.7 | 221.0 | 140.8 | 20.6 | 47.1 | 4.4 | 37.4 | 1,354.9 |
| Africa | 1,028.2 | 22.4 | 468.4 | 80.0 | 83.3 | 34.1 | 42.1 | 52.0 | 1,810.6 |
| Asia | 1,900.6 | 166.1 | 556.2 | 188.0 | 74.4 | 62.1 | 41.7 | 100.0 | 3,089.1 |
| Australia | 629.6 | 11.3 | 177.7 | 23.8 | 28.3 | 14.1 | 4.9 | 4.3 | 893.9 |
| Grand Total | 7,569.2 | 394.7 | 2,214.2 | 664.1 | 297.3 | 247.5 | 147.7 | 298.4 | 11,833.1 |
| **Percent of length category** | **95.0** | **5.0** | **76.9** | **23.1** | **54.6** | **45.4** | **33.1** | **66.9** |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| **Future scenario** | |  |  |  |  |  |  |  |  |
|  | 10-100 km | | 100-500 km | | 500-1000 km | | > 1000 km | | Grand Total |
|  | FF | Not FF | FF | Not FF | FF | Not FF | FF | Not FF |  |
| North America | 1,363.4 | 73.4 | 373.0 | 149.4 | 28.8 | 55.8 | 13.1 | 63.2 | 2,120.2 |
| South America | 1,814.7 | 70.6 | 360.6 | 139.3 | 41.1 | 55.1 | 14.2 | 68.8 | 2,564.4 |
| Europe | 798.4 | 85.3 | 211.6 | 150.1 | 20.6 | 47.1 | 4.4 | 37.4 | 1,354.9 |
| Africa | 1,025.1 | 25.5 | 447.4 | 101.1 | 71.4 | 46.1 | 22.6 | 71.5 | 1,810.6 |
| Asia | 1,889.4 | 177.2 | 533.3 | 210.8 | 65.9 | 70.6 | 31.3 | 110.5 | 3,089.1 |
| Australia | 629.0 | 11.9 | 176.3 | 25.1 | 27.1 | 15.2 | 4.9 | 4.2 | 893.9 |
| Grand Total | 7,520.0 | 443.9 | 2,102.3 | 775.9 | 254.9 | 289.9 | 90.5 | 355.7 | 11,833.1 |
| **Percent of length category** | **94.4** | **5.6** | **73.0** | **27.0** | **46.8** | **53.2** | **20.3** | **79.7** |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| **Difference** |  |  |  |  |  |  |  |  |  |
|  | 10-100 km | | 100-500 km | | 500-1000 km | | > 1000 km | |  |
|  | FF | Not FF | FF | Not FF | FF | Not FF | FF | Not FF |  |
| North America | -.8 | .8 | -4.0 | 4.0 | 0 | 0 | -1.2 | 1.2 |  |
| South America | -23.0 | 23.0 | -53.2 | 53.2 | -20.7 | 20.7 | -26.0 | 26.0 |  |
| Europe | -10.6 | 10.6 | -9.3 | 9.3 | 0 | 0 | 0 | 0 |  |
| Africa | -3.1 | 3.1 | -21.0 | 21.0 | -12.0 | 12.0 | -19.5 | 19.5 |  |
| Asia | -11.2 | 11.2 | -22.9 | 22.9 | -8.6 | 8.6 | -10.5 | 10.5 |  |
| Australia | -.6 | .6 | -1.3 | 1.3 | -1.2 | 1.2 | 0 | 0 |  |
| Grand Total | -49.2 | 49.2 | -111.8 | 111.8 | -42.4 | 42.4 | -57.3 | 57.3 |  |
| **Percent of length category** | **-0.6** | **0.6** | **-3.9** | **3.9** | **-7.8** | **7.8** | **-12.8** | **12.8** |  |
|  |  |  |  |  |  |  |  |  |  |

**Table S3.** List of rivers longer than 500 km, by continent, that changed status from free-flowing to non-free-flowing.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **River Identifier** | **River Basin name** | **River Name** | **Number of projects planned on river** | **River length (km)** | **Discharge at outlet (m3/s)** | **Direct connection to ocean** |
| 2940042 | Amazon | Amazon | 13 | 5990 | 205604 | 1 |
| 2982281 | Amazon | Purus | 1 | 3229 | 6370 | 0 |
| 2971685 | Amazon | Rio Negro | \* | 2375 | 29608 | 0 |
| 3238386 | Amazon | Marañón | 28 | 1666 | 17879 | 0 |
| 3128253 | Amazon | Beni | 2 | 1445 | 8525 | 0 |
| 2995225 | Amazon | Uraricoera | 1 | 1330 | 4914 | 0 |
| 3137879 | Amazon | Madre de Dios | 1 | 1252 | 6214 | 0 |
| 3001067 | Amazon | Arinos | 6 | 1204 | 4458 | 0 |
| 2987316 | Amazon | Roosevelt | \* | 1178 | 4168 | 0 |
| 3258641 | Amazon | Huallaga | 3 | 1130 | 3955 | 0 |
| 3214446 | Amazon | Napo | 2 | 1102 | 7148 | 0 |
| 3051685 | Amazon | Jiparaná | 7 | 935 | 2474 | 0 |
| 3307130 | Amazon | Urubamba | 8 | 892 | 2235 | 0 |
| 2940454 | Amazon | Jari | 4 | 845 | 1213 | 0 |
| 3264852 | Amazon | Pastaza | 3 | 798 | 2326 | 0 |
| 3024535 | Amazon | Aripuanã | 1 | 789 | 1995 | 0 |
| 2944844 | Amazon | Trombetas | 1 | 783 | 4097 | 0 |
| 3051047 | Amazon | Ituxi | \* | 721 | 1203 | 0 |
| 2958620 | Amazon | Jamanxim | 9 | 666 | 2215 | 0 |
| 3312799 | Amazon | Ucayali | 1 | 657 | 1313 | 0 |
| 3049896 | Amazon | Juruena | 13 | 628 | 2269 | 0 |
| 3244643 | Amazon | Caqueta | 1 | 620 | 2410 | 0 |
| 3058517 | Amazon | Sangue | 9 | 530 | 606 | 0 |
| 3278138 | Amazon | Santiago | 10 | 526 | 1258 | 0 |
| 2942726 | Amazon | Cuminapanema | \* | 521 | 470 | 0 |
| 3266574 | Amazon | Aguaricol | 2 | 510 | 815 | 0 |
| 2954257 | Amazon | Mapuera | 1 | 507 | 686 | 0 |
| 3190559 | Amazon | Tarauaca | 1 | 505 | 621 | 0 |
| 3047218 | Amazon | Mucajaí | 3 | 500 | 450 | 0 |
| 1647190 | Amur | Onon Gol | 2 | 1573 | 571 | 0 |
| 1634044 | Amur | Selemdzha | 1 | 653 | 612 | 0 |
| 361725 | Bandama | Nzi | \* | 669 | 154 | 0 |
| 2373529 | Baram | Baram | 1 | 550 | 946 | 1 |
| 430829 | Cavalla | Cavally | 1 | 701 | 926 | 1 |
| 496373 | Congo | Congo | 3 | 4960 | 39637 | 1 |
| 503252 | Congo | Ubongi | 1 | 2641 | 5167 | 0 |
| 501345 | Congo | Dja | 1 | 1463 | 3341 | 0 |
| 586857 | Congo | Lukanga | \* | 1186 | 1769 | 0 |
| 519500 | Congo | Lulua | 1 | 1147 | 456 | 0 |
| 549859 | Congo | Mbomou | \* | 905 | 1317 | 0 |
| 546780 | Congo | Lindi | 1 | 849 | 996 | 0 |
| 534240 | Congo | Tshiumbe | 1 | 730 | 402 | 0 |
| 531186 | Congo | Tshikapa | 1 | 707 | 159 | 0 |
| 565609 | Congo | Ulindi | \* | 652 | 902 | 0 |
| 533582 | Congo | Luachimo | 1 | 623 | 176 | 0 |
| 306868 | Corubal | Koumba | 1 | 752 | 331 | 1 |
| 2888025 | Essequibo | Essequibo | \* | 918 | 3935 | 1 |
| 2888026 | Essequibo | Cuyuni | \* | 762 | 2081 | 0 |
| 2888033 | Essequibo | Mazaruni | 3 | 585 | 1050 | 0 |
| 276519 | Gambia | Gambia | 1 | 1107 | 143 | 1 |
| 2018264 | Ganges | Bibiyana | 1 | 915 | 5600 | 0 |
| 2025343 | Ganges | Arun | 4 | 824 | 2293 | 0 |
| 2033083 | Ganges | Kali Gandaki | 10 | 765 | 1845 | 0 |
| 2040810 | Ganges | Rapti | 2 | 724 | 579 | 0 |
| 2052378 | Ganges | Subsansiri | 1 | 541 | 2967 | 0 |
| 2052932 | Ganges | Kali | \* | 525 | 576 | 0 |
| 4113059 | Grande de Matagalpa | Grande | 2 | 533 | 604 | 1 |
| 2003170 | Indus | Shyok | \* | 704 | 133 | 0 |
| 2213941 | Irrawaddy | Irrawaddy | 7 | 2071 | 17182 | 1 |
| 2216970 | Irrawaddy | Chindwin | 2 | 1201 | 5664 | 0 |
| 454398 | Jubba | Jubba | 1 | 1556 | 316 | 0 |
| 441432 | Kerio | Omo | 3 | 1191 | 963 | 0 |
| 287251 | Komadugu Yobe | Logone | 2 | 1035 | 341 | 0 |
| 491491 | Kouilou | Kouilou-Niari | 2 | 756 | 966 | 1 |
| 1305242 | Lena | Aldan | \* | 2363 | 5274 | 0 |
| 1337613 | Lena | Timpton | 1 | 623 | 537 | 0 |
| 632982 | Lurio | Lurio | 2 | 646 | 686 | 1 |
| 4162481 | Mackenzie | Liard | 1 | 1245 | 2441 | 0 |
| 3381390 | Mearim | Grajaú | 1 | 532 | 336 | 0 |
| 2293219 | Mekong | Xé Kong | 5 | 543 | 1077 | 0 |
| 420060 | Niger | Bani | \* | 1139 | 207 | 0 |
| 83692 | Nile | Semtiki | 1 | 673 | 329 | 0 |
| 60175 | Nile | Baro Wenz | 6 | 555 | 296 | 0 |
| 445344 | Nyong | Nyong | 1 | 671 | 595 | 1 |
| 704484 | Okwa | Okavango | 1 | 2090 | 103 | 0 |
| 711465 | Okwa | Kuito | \* | 837 | 74 | 0 |
| 2819756 | Orinoco | Meta | 8 | 1050 | 5288 | 0 |
| 3510953 | Parana | Pilcomayo | 4 | 1660 | 59 | 0 |
| 3507918 | Parana | Ivaí | 3 | 701 | 726 | 0 |
| 3517449 | Parana | Rio Paraguai | 1 | 669 | 1168 | 0 |
| 3505443 | Parana | Piquiri | 3 | 575 | 607 | 0 |
| 3521908 | Parana | Braco do Sao Lourenco | 6 | 545 | 649 | 0 |
| 2550025 | Purari | Purari | 1 | 623 | 1564 | 1 |
| 611812 | Rufiji | Ruhudji | 1 | 614 | 821 | 0 |
| 2200164 | Salween | Salween | 16 | 3244 | 5218 | 1 |
| 3605728 | Santa Cruz | Santa Cruz | 3 | 586 | 711 | 1 |
| 3396737 | Sao Francisco | Grande | 2 | 522 | 426 | 0 |
| 2273831 | Tenasserim | Tenasserim | 1 | 543 | 913 | 1 |
| 3355836 | Tocantins | Pãrana | 5 | 606 | 610 | 0 |
| 2178508 | Xe Xongka | Sông Ca | 4 | 525 | 649 | 1 |
| 1446212 | Yenisey | Egiyn Gol | \* | 662 | 111 | 0 |
| 682959 | Zambezi | West Lunga | \* | 662 | 431 | 0 |

\* no planned projects on river main stem, but river is affected by hydropower projects upstream or downstream due to impacts from fragmentation (DOF), flow regulation (DOR), or sediment trapping (SED)