Fragmentation and Flow Regulation of River Systems in the Northern Third the World

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# Fragmentation and Flow Regulation of River Systems in the Northern Third of the World

Mats Dynesius and Christer Nilsson*

Seventy-seven percent of the total water discharge of the 139 largest river systems in North America north of Mexico, in Europe, and in the republics of the former Soviet Union is strongly or moderately affected by fragmentation of the river channels by dams and by water regulation resulting from reservoir operation, interbasin diversion, and irrigation. The remaining free-flowing large river systems are relatively small and nearly all situated in the far north, as are the 59 medium-sized river systems of Norway, Sweden, Finland, and Denmark. These conditions indicate that many types of river ecosystems have been lost and that the populations of many riverine species have become highly fragmented. To improve the conservation of biodiversity and the sustainable use of biological resources, immediate action is called for to create an international preservation network of free-flowing river systems and to rehabilitate exploited rivers in areas that lack unaffected watercourses.

Natural rivers, including their riparian zones, belong to the most diverse, dynamic, and complex ecosystems on the world's continents (1). At the same time, the damming of rivers has been identified as one of the most dramatic and widespread deliberate impacts of humans on the natural environment (2). The area of former terrestrial habitat inundated by all large ($>10^8$ $m^3$) reservoirs in the world is comparable with the area of California or France (3). Damming and diversion have greatly changed the conditions for riparian and aquatic organisms in standing as well as flowing waters (4) in three major ways: The habitats for organisms adapted to natural discharge and water-level regimes are impoverished (2, 4–7), the ability of each river to serve as a corridor is reduced (8, 9), and the function of the riparian zone as a filter between upland and aquatic systems is greatly modified (10). These adverse ecological effects have only recently been recognized (2, 5–7). The need to preserve free-flowing rivers, representing different geomorphic settings and biomes, has now been accentuated (11), and the rehabilitation of degraded rivers has been initiated in many countries (12).

Assessments of human impacts over large areas are necessary for successful environmental management, and such studies are being produced at an increasing rate (13). However, assessments of the direct human-induced changes of the river flow and river channel continuity of all large river systems are lacking [but see, for example, (3) for gross global assessments], as are complete and reliable lists of large river systems in terms of the discharge. We compiled such data for all large river systems in the northern third of the world using a large amount of information from publications, experts, and agencies (14–17). These data were reviewed by several experts and agencies and provided the basis for sorting the river systems into three classes of exploitation: strong, moderate, and no impact. To test whether the obtained patterns also apply at a higher resolution, we made a similar study incorporating the medium-sized rivers of Norway, Sweden, Finland, and Denmark.

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## Background

River systems and their riparian zones play key roles in the regulation and maintenance of biodiversity in the landscapes. They have a fundamental role in the movement of organisms and dead matter (8), being the most important natural corridors through the landscape (18). Ecologists now view rivers both as systems with their own characteristics and as mediators of communication in several dimensions. Ecological interactions can be apprehended in both directions between the river and the receiving sea, the main river channel and its tributaries, the river's source and mouth (9), the river and its terrestrial surroundings (10), the river and the atmosphere, and even the river and the hyporheic water (that is, water moving underground) (19). Therefore, evaluations of the environmental impacts of human activities as well as strategies for river conservation should use the whole river basin as the basic functional unit of river landscapes (20).

The expansion of human populations and activities has resulted in extensive damming, regulation, and diversion of the world's rivers. The number of large dams in the world has increased sevenfold from 1950 to 1986, up to about 39,000 (21). The usable man-made reservoir capacity in relation to the annual river runoff is about 9% on a world basis, 10% in Europe, and 22% in North America (3). Diversion schemes have become common, and in Canada 4400 $m^3$ of water is diverted each second and not returned to the stream of origin (22), equaling twice the discharge of the Nile. As much as 6% of the world's river runoff is evaporated through human manipulations, mainly by irrigation but also by evaporation from reservoirs (3). From the Colorado River system 64% of the runoff is consumed by irrigation, and an additional 32% is lost by evaporation from reservoirs (23); little water reaches the Gulf of California.

## Size and Location

The term "river" may refer to the segment of a river channel bearing a particular name, to the entire main channel, or to a tributary. Hence, we use the term "river system" throughout to emphasize the fact that we studied entire networks of stream and river channels interconnected by surface freshwater, from the headwaters to the sea (24). There are also many different ways of defining river size. Easily assessed variables such as main channel length or catchment area are often used. However, several ecological studies suggest that the structure of riverine ecosystems is strongly correlated with water discharge (25, 26). For most rivers, the highest discharge is found close to the receiving sea, but in arid areas, discharge decreases naturally downstream. We defined a large river system (LRS) as a system that has, anywhere in its catchment, a river channel section with a virgin mean annual discharge (VMAD, the discharge before any significant direct human manipulations) of at least 350 $m^3$ $s^{-1}$. We set the corresponding lower limit of a medium-sized river system (MRS) to 40 $m^3$ $s^{-1}$ (27).

We limited our study to Europe, the former Soviet Union, and North America north of Mexico, or the northern third of the world's land (including Antarctica). There are 139 LRSs with either their mouths or more than half of their catchments within this area (Table 1 and Figs. 1 and 2). These LRSs have a total VMAD of nearly 254,000 $m^3$ $s^{-1}$, or 20% of the world's river runoff. North America has 74 and Eurasia has 65 LRSs, but the Eurasian LRSs have a 21% higher total VMAD (139,000 versus 115,000 $m^3$ $s^{-1}$) because the average Eurasian system has a 37% larger VMAD than its North American

**Table 1.** River systems in the northern third of the world with a VMAD of 350 $m^3 s^{-1}$ or more (*14*, *15*), as well as assessments of fragmentation by dams in the main channel and in tributaries and of flow regulation (*16*, *17*) for each river system. VMAD refers to the most water-rich river channel section, in most cases close to the estuary, before any significant direct human manipulation. The main channel is the channel having the highest VMAD. The river systems are grouped by continent and impact class as defined in Table 5. The numbers beside each river system refer to those in Figs. 1 and 2. Fragmentation is ranked into five classes describing the longest main-channel segment without dams (but frequently including reservoir water tables) in relation to the entire main channel (0 = 100%; 1 = 75 to 99%; 2 = 50 to 74%; 3 = 25 to 49%; and 4 = 0 to 24%). For the tributaries, fragmentation is described by three classes (0 = no dams; 1 = dams only in the catchment of minor tributaries; and 2 = dams also in the catchment of the largest tributary). Flow regulation is described by reservoir live storage (reserv. live stor.), reservoir gross capacity (reserv. gross cap.), interbasin diversion (interb. div.), and irrigation consumption (irrig. consumpt.) for the entire river system expressed as the percent of its VMAD. 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. A "+" sign after the live storage value means that the corresponding gross capacity value represents additional reservoirs where data on live storage is lacking. Interbasin diversions are those in which water is transferred to (+) and from (−) the river system. Irrigation consumption is the water consumed by evaporation and evapotranspiration from irrigated land. Where only gross statements are available, irrigation consumption is described by "+" (minor) or "++" (major). An additional 32% of the runoff from the Colorado River and 1.3% from the Mississippi River are consumed by increased evaporation from reservoirs. With regard to the data on the Amur, Ob, Kura, Amu-Dar'ya, Ili, and Yenisey river systems, conditions in Turkey, Afghanistan, Iran, China, and Mongolia are not included in our study, but these will not change the classification for any river.

| River system | VMAD ($m^3 s^{-1}$) | Fragmentation | | Flow regulation (% of VMAD) | | | |
|---|---|---|---|---|---|---|---|
| | | Main channel | Tributary | Reserv. live stor. | Reserv. gross cap. | Interb. div. | Irrig. consumpt. |
| *North America: not affected* | | | | | | | |
| 7. Skeena | 1760 | 0 | 2 | | 0.2 | | |
| 8. Nass | 892 | 0 | 0 | | | | |
| 9. Stikine | 1600 | 0 | 0 | | | | |
| 10. Taku | ~600 | 0 | 0 | | | | |
| 11. Alsek | ~850 | 0 | 1 | 2 | | | |
| 12. Copper | 1700 | 0 | 0 | | | | |
| 13. Susitna | 1400 | 0 | 0 | | | | |
| 14. Kvichak | 590 | 0 | 0 | | | | |
| 15. Nushagak | 1000 | 0 | 0 | | | | |
| 16. Kuskokwim | 1900 | 0 | 0 | | | | |
| 17. Yukon | 6370 | 0 | 2 | | 0.1 | | |
| 18. Kobuk | ~510 | 0 | 0 | | | | |
| 19. Noatak | ~350 | 0 | 0 | | | | |
| 20. Colville | ~600 | 0 | 0 | | | | |
| 22. Coppermine | 357 | 0 | 0 | | | | |
| 23. Back | 612 | 0 | 0 | | | | |
| 24. Thelon, Kazan | 1370 | 0 | 0 | | | | |
| 25. Thaanne, Thlewiatza | 507 | 0 | 0 | | | | |
| 26. Seal | 365 | 0 | 0 | | | | |
| 29. Hayes | 694 | 0 | 0 | | | | |
| 30. Severn | 722 | 0 | 0 | | | | |
| 31. Winisk | 694 | 0 | 0 | | | | |
| 32. Attawapiskat | 626 | 0 | 0 | | | | |
| 35. Harricana | 473 | 0 | 0 | | | | |
| 37. Broadback | 383 | 0 | 0 | | | | |
| 38. Rupert | 878 | 0 | 0 | | | | |
| 42. Povungnituk | >350 | 0 | 0 | | | | |
| 43. Arnaud | 654 | 0 | 0 | | | | |
| 44. R. aux Feuilles | 575 | 0 | 0 | | | | |
| 46. R. à la Baleine | 581 | 0 | 0 | | | | |
| 47. George | 881 | 0 | 0 | | | | |
| 51. Petit Mécatina | 524 | 0 | 0 | | | | |
| 52. Natashquan | 422 | 0 | 0 | | | | |
| 53. Moisie | 490 | 0 | 0 | | | | |
| 73. Pascagoula | ~430 | 0 | 2 | | 1.6 | | |
| *North America: moderately affected* | | | | | | | |
| 5. Skagit | 475 | 2 | 1 | | 16 | | |
| 6. Fraser | 3620 | 0 | 2 | | 26 | −3 | + |
| 21. Mackenzie | 9910 | 1 | 1 | | ≥24 | | |
| 33. Albany | 1420 | 1 | 2 | | ≥3 | −17 | |
| 36. Nottaway | 1130 | 0 | 2 | | ≥0 | −1.2 | |
| 41. Gr. R. Baleine | 665 | 0 | 1 | | | −4 | |
| 55. R. aux Outardes | 399 | 1 | 0 | | ≥21 | | |
| 63. Hudson | ~620 | 2 | 2 | | 14 | | |
| 64. Delaware | ~550 | 1 | 2 | | 10 | −6 | |
| 65. Susquehanna | 1198 | 2 | 2 | | 4 | | |
| 66. Potomac | ~350 | 3 | 1 | | 3 | | |
| 67. Pee Dee | 552 | 3 | 1 | | 8 | | |
| 70. Altamaha | 406 | 1 | 2 | | 8 | | |
| *North America: strongly affected* | | | | | | | |
| 1. Colorado | 550 | 3 | 2 | | 560 | −40 | 64 |
| 2. Sacramento, San Joaquin | 1140 | 2 | 2 | | 98 | −11, +4 | ++ |
| 3. Klamath | 515 | 3 | 2 | | 31 | −8 | + |
| 4. Columbia | 7500 | 4 | 2 | | ≥48 | | ++ |
| 27. Churchill | 1270 | 2 | 2 | 47 | >125 | −6 | |
| 28. Nelson | 2830 | 3 | 2 | 90 | >112 | +32 | + |
| 34. Moose | 1440 | 3 | 2 | 7 | ≥7 | | |
| 39. Eastmain | 909 | 1 | 2 | 12 | 30 | −93 | |
| 40. La Grande | 1720 | 3 | 1 | 96 | 260 | +97 | |
| 45. Koksoak | 2420 | 2 | 0 | 51 | 70 | −33 | |
| 48. Kanairiktok | ~350 | 1 | 0 | | | −37 | |
| 49. Naskaupi | ~350 | 2 | 0 | | | −57 | |
| 50. Churchill | 1620 | 3 | 2 | 61 | ≥66 | +20 | |
| 54. Manicouagan | 852 | 3 | 1 | | ≥590 | | |
| 56. Betsiamites | 375 | 2 | 0 | | ≥118 | −2 | |
| 57. Saguenay | 1760 | 3 | 1 | | ≥29 | +0.3 | |
| 58. St. Lawrence | 10,800 | 3 | 2 | | ≥22 | −0.8, + >1.6 | 1 |
| 59. St. John | 1100 | 3 | 2 | 2+ | 1 | ~−1 | |
| 60. Penobscot | 450 | 3 | 2 | | 16 | ~+3 | |
| 61. Kennebec, Androscoggin | 488 | 3 | 2 | | 15 | | |
| 62. Connecticut | ~540 | 4 | 2 | | 18 | | |
| 68. Santee | 560 | 3 | 2 | | 60 | −15 | |
| 69. Savannah | 369 | 3 | 2 | | 96 | | |
| 71. Apalachicola | ~750 | 3 | 1 | | 22 | | |
| 72. Mobile | 1900 | 4 | 2 | | 13 | >0 | |
| 74. Mississippi | 18,400 | 3 | 2 | | 31 | −0.2, +0.6 | 8 |
| *Eurasia: not affected* | | | | | | | |
| 84. Kalixälven, | 282 | 0 | 0 | | | | |
| Torneälven | 373 | 0 | 1 | 1 | | | |
| 117. Uda | 800 | 0 | 0 | | | | |
| 118. Tauy | 362 | 0 | 0 | | | | |
| 119. Penzhina | 720 | 0 | 0 | | | | |
| 120. Kamchatka | 1050 | 0 | 0 | | | | |
| 121. Anadyr | 2020 | 0 | 0 | | | | |
| 123. Indigirka | 1700 | 0 | 0 | | | | |
| 124. Yana | 970 | 0 | 0 | | | | |
| 126. Olenek | 1090 | 0 | 0 | | | | |
| 127. Anabar | 432 | 0 | 0 | | | | |
| 128. Khatanga, Popigay | 3200 | 0 | 0 | | | | |
| 129. Taymyra | 990 | 0 | 0 | | | | |
| 130. Pyasina | 2260 | 0 | 0 | | | | |
| 132. Taz | 1540 | 0 | 0 | | | | |
| 133. Pur | 1050 | 0 | 0 | | | | |
| 134. Nadym | 610 | 0 | 0 | | | | |
| 136. Pechora | 4100 | 0 | 0 | | | | |
| 137. Mezen | 880 | 0 | 0 | | | | |
| 139. Onega | 500 | 0 | 0 | | | | |
| *Eurasia: moderately affected* | | | | | | | |
| 75. Ölfusá | 440 | 0 | 2 | 1.2 | 21 | | |
| 87. Narva | 450 | 1 | 0 | <1 | 3 | | |
| 90. Wisla | 1080 | 2 | 2 | 4 | 6 | | |
| 91. Oder | 580 | 2 | 2 | 5 | ≥6 | | |
| 94. Rhein, | 2200 | 2 | 2 | 2+ | ≥2 | | |
| Maas | >325 | ≥0 | 2 | | ≥4 | | |
| 95. Seine | 500 | 1 | 2 | | 5 | | |
| 96. Loire | 900 | 1 | 2 | | ≥3 | −0.8 | 0.9 |

**Table 1 (continued)**

| River system | VMAD ($m^3$ $s^{-1}$) | Fragmentation | | Flow regulation (% of VMAD) | | | |
|---|---|---|---|---|---|---|---|
| | | Main channel | Trib-utary | Reserv. live stor. | Reserv. gross cap. | Interb. div. | Irrig. con-sumpt. |
| *Eurasia moderately affected* | | | | | | | |
| 98. Adour | 360 | 0 | 2 | 0.6+ | • 0.2 | | 0.8 |
| 110. Rioni | 420 | 2 | 1 | <1 | <1 | | <1 |
| 116. Amur | 10,900 | 0 | 2 | 9 | 20 | | |
| 122. Kolyma | 4060 | 1 | 0 | 5 | 11 | | |
| 125. Lena | 16,900 | 0 | 1 | 3 | 7 | | |
| 135. Ob | 12,800 | 2 | 2 | 9 | 15 | 0.5 | <1 |
| 138. Severn. Dvina | 3330 | 1 | 0 | 1 | 1 | | |
| *Eurasia: strongly affected* | | | | | | | |
| 76. Thjórsá | 390 | 3 | 2 | 13 | 30 | | |
| 77. Glommavassdr. | 728 | 4 | 2 | 16 | | | |
| 78. Göta älv | 554 | 3 | 2 | >54 | | | |
| 79. Dalälven | 353 | 3 | 2 | 26 | | | |
| 80. Indalsälven | 448 | 4 | 2 | 40 | | | |
| 81. Ångermanälven | 481 | 4 | 2 | 43 | | −7, +7 | |
| 82. Umeälven | 435 | 4 | 1 | 27 | | | |
| 83. Luleälven | 500 | 3 | 2 | 72 | | −2 | |
| 85. Kemijoki | 553 | 2 | 1 | 23 | | | |
| 86. Neva | 2490 | 3 | 2 | 4+ | ≥26 | | |
| 88. Daugava | 640 | 3 | 2 | 1 | 8 | | |
| 89. Nemunas | 620 | 3 | 2 | 1 | 5 | | |
| *Eurasia: strongly affected* | | | | | | | |
| 92. Elbe | 750 | 2 | 2 | 10+ | 5 | | |
| 93. Weser | 360 | 4 | 2 | | 5 | | |
| 97. Garonne, Dordogne | 1045 | 3 | 2 | 6+ | 0.9 | | 0.3 |
| 99. Duero/Douro | 650 | 3 | 2 | 62 | ≥21 | | |
| 100. Tajo/Tejo | 500 | 4 | 2 | 50 | ≥34 | −4 | |
| 101. Ebro | 577 | 4 | 2 | 46 | ≥9 | −2 | 24 |
| 102. Rhone | 1900 | 4 | 2 | 2+ | ≥7 | | |
| 103. Po | 1460 | 3 | 2 | 4 | | | |
| 104. Neretva | 378 | 3 | 2 | 7 | 8 | | |
| 105. Drin | ~350 | ≥3 | 2 | | ≥39 | | |
| 106. Danube | 6450 | 3 | 2 | 0.1+ | ≥9 | | |
| 107. Dnepr | 1700 | ≥3 | ≥1 | 35 | 85 | | 9 |
| 108. Don | 890 | ≥1 | ≥1 | 51 | 95 | | 9 |
| 109. Kuban' | 430 | ≥1 | ≥1 | 23 | 37 | | 24 |
| 111. Kura | 850 | ≥3 | 2 | 44 | 75 | | 35 |
| 112. Volga | 8050 | 4 | 2 | 34 | 75 | | 2 |
| 113. Amu-Dar'ya | 2200 | ≥1 | 2 | 14 | 24 | | 50 |
| 114. Syr-Dar'ya | 1170 | ≥3 | 2 | 55 | 75 | | 80 |
| 115. Ili | 570 | ≥2 | ≥1 | 37 | 150 | | 16 |
| 131. Yenisey | 20,000 | ≥2 | 2 | 18 | 58 | | |

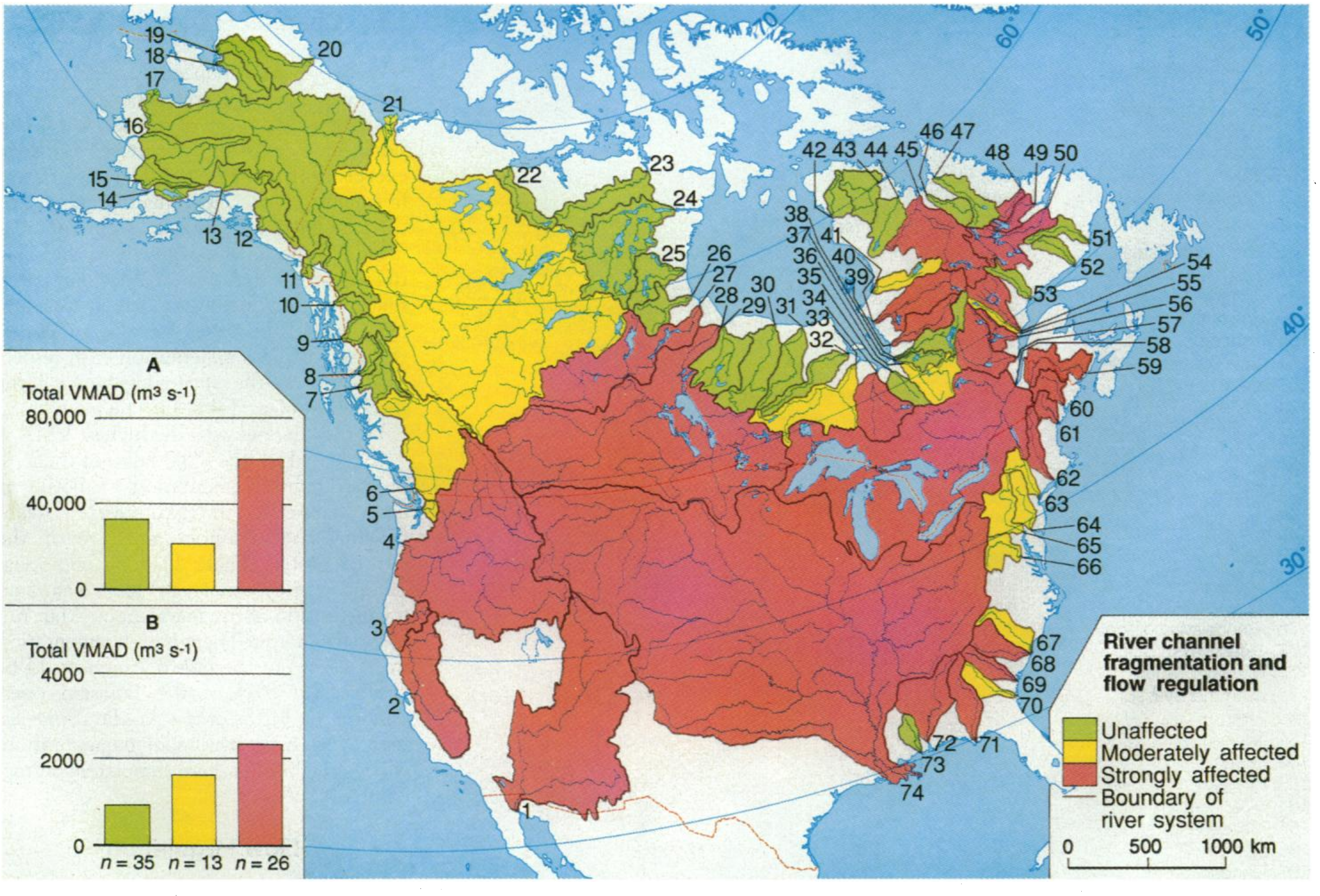


**Fig. 1.** Impact by river channel fragmentation and water flow regulation on the 74 LRSs (VMAD ≥ 350 $m^3$ $s^{-1}$) of North America north of Mexico. River systems are treated as units and are represented on the map by their catchments. White areas indicate land not covered by large river systems and land south of the study area. Diagrams present (**A**) total VMAD of all rivers and (**B**) VMAD per river system in each impact class. Impact classes are defined in Table 5, and river system numbers refer to those in Table 1. There are no LRSs on Greenland.

**Table 2.** River systems in Norway, Sweden, Finland, and Denmark with 40 $m^3$ $s^{-1}$ < VMAD < 350 $m^3$ $s^{-1}$ (*15*), and an assessment of fragmentation by dams in the main channel and in tributaries and of flow regulation (*17*) for each river system. The main channel is the one having the highest VMAD. River systems are grouped by impact class (Table 5). The numbers beside each system refer to Fig. 3. Fragmentation is defined in Table 1. For interbasin diversions, water transfers to (+) and from (−) the river system are indicated. There is no significant irrigation.

| River system | VMAD ($m^3$ $s^{-1}$) | Fragmentation | | Flow regulation (% of VMAD) | |
|---|---|---|---|---|---|
| | | Main channel | Tributary | Reserv. live stor. | Interb. div. |
| | | *Not affected* | | | |
| 141. Tana/Tenojoki | 187 | 0 | 0 | | |
| 146. Saltdalsvassdraget | 50 | 0 | 1 | 0.2 | |
| 152. Snåsavassdraget | 75 | 0 | 0 | | +9 |
| 153. Verdalsvassdraget | 65 | 0 | 0 | | |
| 163. Gaularvassdraget | 55 | 0 | 0 | | |
| 189. Byskeälven | 41 | 0 | 0 | | |
| 191. Råneälven | 42 | 0 | 0 | | |
| 192. Simojoki | 44 | 0 | 0 | | |
| 194. Kiiminkijoki | 44 | 0 | 0 | | |
| | | *Moderately affected* | | | |
| 142. Altavassdraget | 84 | 1 | 0 | 5 | |
| 143. Reisavassdraget | 43 | 0 | 1 | 0.7 | −3.5, +0.9 |
| 144. Målselvvassdraget | 180 | 0 | 2 | 21 | |
| 147. Beiarelva | 48 | 1 | 1 | | −15 |
| 150. Vefsna | 161 | 0 | 1 | | −7 |
| 154. Stjørdalsvassdraget | 82 | 2 | 1 | 8 | |
| 156. Gaula | 98 | 0 | 1 | 5 | |
| 158. Surna | 59 | 0 | 2 | 21 | |
| 159. Driva | 69 | 0 | 1 | 13 | +3 |
| 160. Rauma | 41 | 0 | 1 | 3 | +22 |
| 161. Breimsvassdraget | 43 | 1 | 0 | 3 | |
| 162. Jølstra | 54 | 2 | 0 | 3 | |
| 170. Bjerkreimsvassdr. | 57 | 2 | 0 | 4 | |
| 175. Tovdalsvassdraget | 64 | 0 | 2 | 5 | |
| 190. Piteälven | 155 | 1 | 1 | 4 | |
| 193. Iijoki | 172 | 2 | 1 | 9 | |
| 196. Kyrönjoki | 44 | 2 | 2 | 5 | |
| | | *Strongly affected* | | | |
| 140. Pasvikelva/Paatsjoki | 170 | 2 | 1 | 48 | |
| 145. Sulitjelmavassdraget | 40 | 4 | 2 | 63 | −13 |
| 148. Ranavassdraget | 220 | 2 | 1 | 34 | −12, +23 |
| 149. Røssåga | 96 | 2 | 1 | 85 | −4, +16 |
| 151. Namsen | 270 | 3 | 1 | 14 | −14, +13 |
| 155. Nidelvvassdraget | 117 | 3 | 2 | 38 | |
| 157. Orkla | 70 | 3 | 2 | 19 | |
| 164. Jostedøla | 60 | 1 | 1 | 36 | |
| 165. Årdalsvassdraget | 44 | 1 | 2 | 26 | −5 |
| 166. Vossovassdraget | 104 | 2 | 1 | 8 | −4, +15 |
| 167. Eidfjordvassdraget | 50 | 2 | 1 | 28 | −41 |
| 168. Suldalsvassdraget | 103 | 3 | 2 | 28 | −78, +68 |
| 169. Årdalselva | 45 | 2 | 2 | 40 | −55 |
| 171. Sira | 116 | 3 | 2 | 53 | −5, +44 |
| 172. Kvina | 87 | 3 | 0 | 41 | −59, +6 |
| 173. Mandalselva | 85 | 3 | 2 | 14 | |
| 174. Otra | 148 | 3 | 2 | 42 | −6 |
| 176. Arendalsvassdraget | 119 | 3 | 2 | 36 | |
| 177. Skiensvassdraget | 287 | 3 | 2 | 47 | |
| 178. Numedalslågen | 119 | 3 | 2 | 25 | −0.8 |
| 179. Drammensvassdr. | 326 | 3 | 2 | 34 | +0.3 |
| 180. Ätran | 47 | 3 | 2 | >4 | |
| 181. Nissan | 40 | 3 | 2 | >0.2 | |
| 182. Lagan | 72 | 3 | 2 | >18 | |
| 183. Helgeån | 44 | 3 | 2 | >0.5 | |
| 184. Motala ström | 91 | 3 | 2 | >7 | |
| 185. Mälaren-Norrström | 166 | 3 | 2 | >5 | |
| 186. Ljusnan | 219 | 4 | 2 | 22 | |
| 187. Ljungan | 136 | 4 | 2 | 29 | |
| 188. Skellefteälven | 155 | 4 | 2 | 62 | |
| 195. Oulujoki | 254 | 3 | 2 | 52 | |
| 197. Kokemäenjoki | 226 | 3 | 2 | 18 | |
| 198. Kymijoki | 303 | 3 | 2 | 21 | |

counterpart. In Norway, Sweden, Finland, and Denmark there are 59 MRSs (Table 2, Fig. 3) contributing 38% more runoff than the nine LRSs within the same area (6500 versus 4700 $m^3$ $s^{-1}$).

The catchments of the 139 LRSs span all 10 different biomes (*28*) of the study area, from tundra to warm desert (Table 3). The biomes are represented by 46 out of 52 different biogeographic provinces: 18 in the Nearctic and 28 in the Palearctic realm. Half of the LRSs have catchments dominated by temperate needle-leaf forests or woodlands, a biome that also covers minor parts of an additional 11% of the LRSs. The biogeographic province holding most LRSs, dominating 36 and covering parts of another 5, is the Canadian taiga. In the Palearctic realm, the West Eurasian taiga covers at least parts of 21 river systems and dominates 18 of those. The Yenisey and Ob river systems encompass the widest biogeographic variation with six biogeographic provinces each (Table 4). In North America, the catchment of the Mississippi River extends over five biogeographic provinces.

## Channel Fragmentation

We assessed dam-induced fragmentation of the river channel corridor, but not, for example, fragmentation of riparian forest corridors by forestry or agriculture. All dams except low weirs were considered to have a fragmenting effect. The main channel and the tributaries were assessed separately. We measured the longest segment of the main river channel that was without dams (but that frequently included reservoir water tables) using five classes, and for tributaries we assessed the fragmentation with respect to the size of the affected tributary using three classes (see Table 1). The main channel is the channel with the highest VMAD.

At least 11 LRSs (8%) fall into the class of maximum fragmentation of both the main channel and the tributaries (*29*), eight of which are in Europe and three in the United States (Table 1). One additional European LRS (Umeälven) has a maximum fragmentation of the main channel but not of the tributaries. There is no fragmentation in 31 (42%) of the North American LRSs or in 18 (28%) of the Eurasian ones. Among the MRSs of the Nordic countries, four (7%) have maximum fragmentation, whereas eight (14%) are completely unfragmented (Table 2).

## Flow Regulation

We assessed three types of human manipulations of the flow regime: reservoirs, intersystem water transfer, and irrigation consumption. We quantified the impact of the reservoirs by their summed capacity, irrespective of their location in the catchment. This measure is expressed as the percentage of one average year's discharge of the river system that can be contained in the reservoirs. Available capacity data are inconsistent. Some references give "gross capacity," whereas others give "live" or "active" storage. The latter measure is preferable because it includes only the volume that can be withheld in, and subsequently released from, the reservoir. Gross capacity also includes bottom water below the invert level of the lowest outlet, so-called "dead storage," that cannot be used for regulation.

The highest live storage value is registered for La Grande Rivière in Québec (96%), and the highest gross capacity is found in Rivière Manicouagan (590%), also in Québec (Table 1). In Eurasia, the highest recorded live storage for an LRS is 72% (Luleälven in Sweden) and the highest gross capacity for an LRS is 150% (Ili in Kazakhstan). The medium-sized Røssåga system in Norway has a live storage of as much as 85% (Table 2).

We define intersystem water transfers or interbasin diversions as water transferred from one river system to another or through a man-made shortcut to the sea. Irrigation consumption refers to the amount of water evaporated or evapotranspirated as a result of irrigation and excludes water returned from irrigated land to the river system. We also express the average amount of water transferred or consumed as a percentage of one year's discharge of the river system (in some cases only gross statements such as "major" or "minor" are available). The highest interbasin diversion percentages are also recorded for La Grande project in Québec: Rivière Eastmain loses 93% of its wa-

**Table 3.** Representation of biomes (*28*) in the catchments of the 139 largest river systems of the northern third of the world and the impact class distribution (Table 5) of the river systems that lie at least in part within each biome. For the number of river systems, the first value in parentheses represents the river systems where the biome dominates, whereas the second value in parentheses represents those where the biome covers a minor portion. Each river system flows through between one and five biomes. Biomes are listed in order of increasing degree of river system exploitation. The "northern biogeographic provinces" include the Icelandian, Subarctic birchwoods, and Kamchatkan provinces.

| Biome | Number of river systems | Impact class distribution of the river systems | | |
|---|---|---|---|---|
| | | Not affected (%) | Moderately affected (%) | Strongly affected (%) |
| Tundra and barren arctic | 42 (14 + 28) | 79 | 10 | 12 |
| Subtropical and temperate rain forests | 10 (1 + 9) | 70 | 10 | 20 |
| Temperate needle-leaf forests | 85 (69 + 16) | 53 | 13 | 34 |
| Temperate broad-leaf forests, and subpolar deciduous thickets | | | | |
| Northern provinces | 5 (3 + 2) | 40 | 20 | 40 |
| Southern provinces | 37 (28 + 9) | 3 | 38 | 59 |
| Mixed mountain and highland systems | 29 (16 + 13) | 14 | 24 | 62 |
| Temperate grasslands | 11 (3 + 8) | 0 | 27 | 73 |
| Evergreen sclerophyllous forests | 11 (4 + 7) | 0 | 18 | 82 |
| Cold-winter (continental) deserts | 8 (1 + 7) | 0 | 0 | 100 |
| Lake systems | 5 (0 + 5) | 0 | 0 | 100 |
| Warm deserts | 1 (0 + 1) | 0 | 0 | 100 |
| All river systems | | 39 | 19 | 42 |

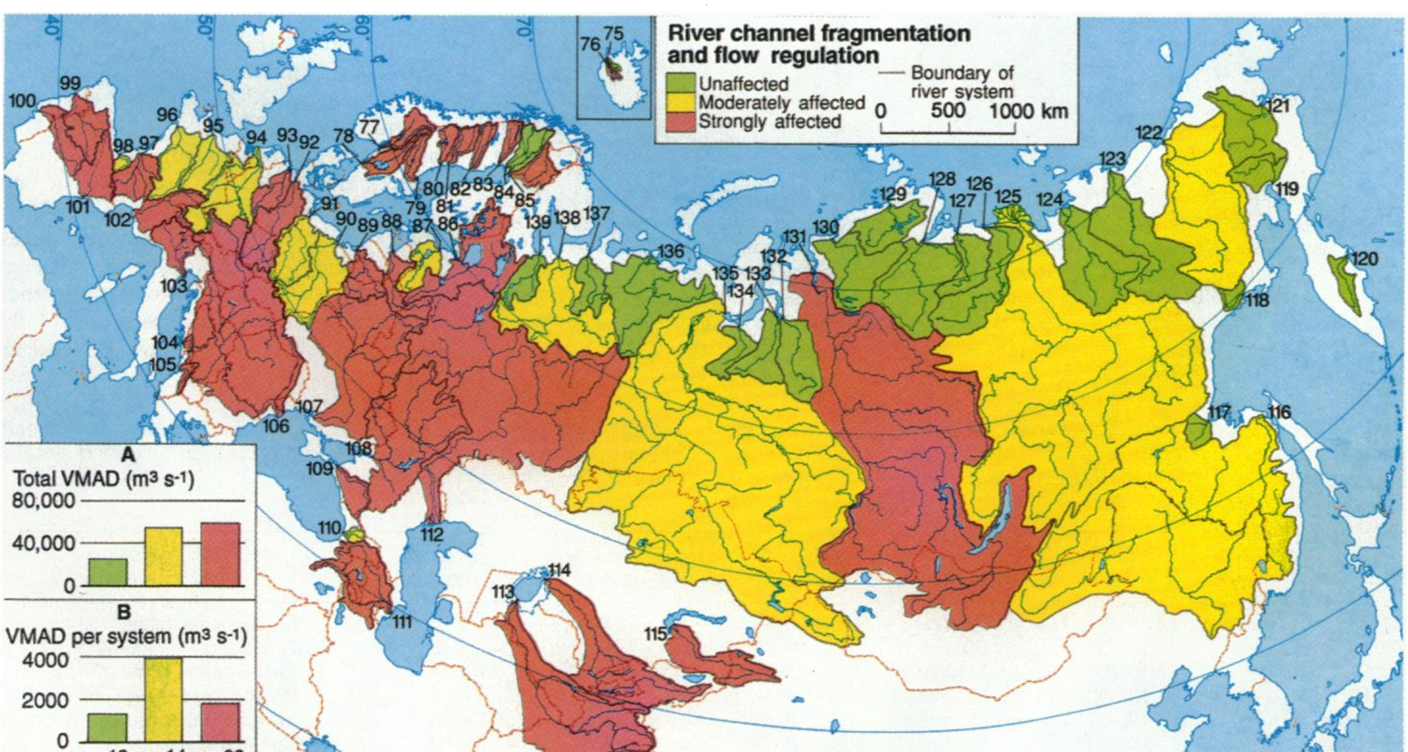


**Fig. 2.** Impact by river channel fragmentation and flow regulation on the 65 LRSs (VMAD ≥ 350 $m^3 s^{-1}$) of Europe and the republics of the former Soviet Union. River systems are treated as units and are represented on the map by their catchments. White areas indicate land not covered by LRSs and land south of the study area. Diagrams present (**A**) total VMAD of all rivers and (**B**) VMAD per river system in each impact class. Impact classes are defined in Table 5, and river system numbers refer to those in Table 1.

ter, and La Grande Rivière gains 97% on top of its original discharge (Table 1). In Eurasia, the highest recorded interbasin diversion is in the Norwegian MRS Suldalsvassdraget, which gains 68% and loses 78% of its VMAD (Table 2). The largest irrigation consumption (80%) is recorded for Syr-Dar'ya, causing large problems in the Aral Lake area (*30*), whereas cold and humid areas have little irrigation (Table 1).

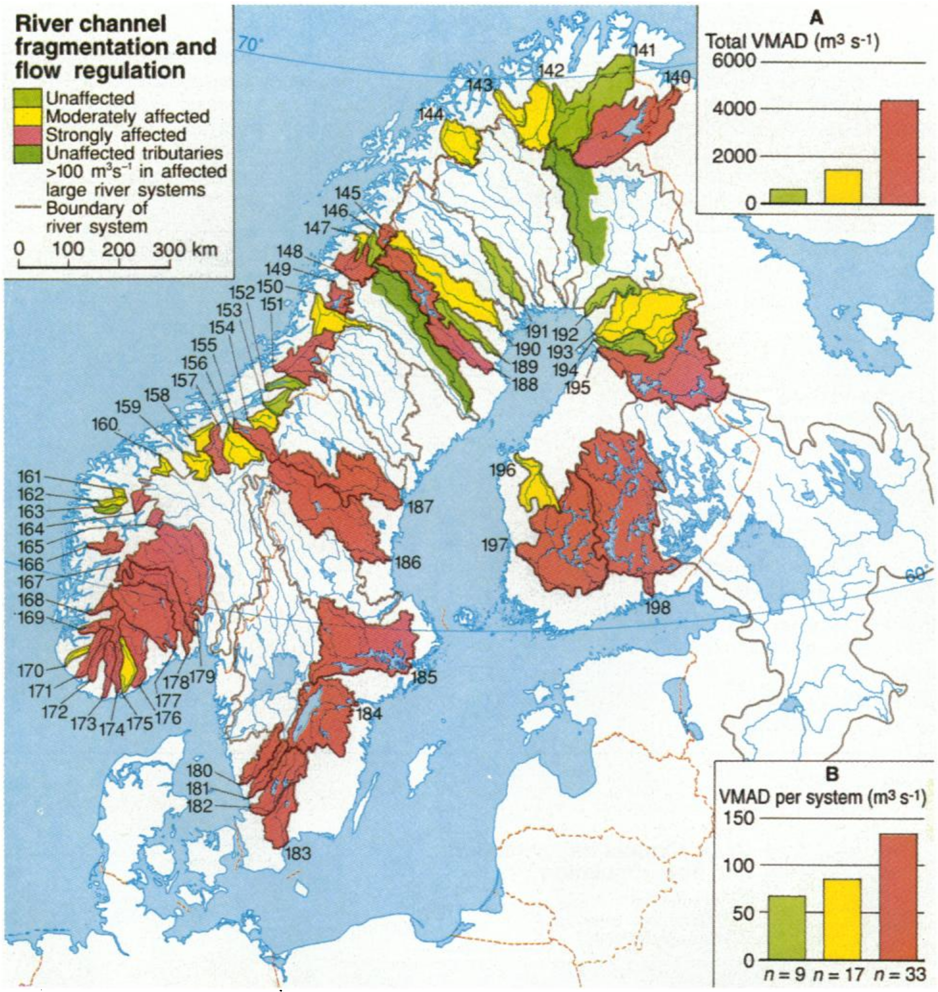


**Fig. 3.** Impact by river channel fragmentation and flow regulation on the 59 MRSs (40 ≤ VMAD < 350 m$^3$ s$^{-1}$) of Norway, Sweden, Finland, and Denmark (Denmark's largest river system has a flow of only ~30 m$^3$ s$^{-1}$). River systems are treated as units and are represented on the map by their catchments. White areas indicate land not covered by MRSs and land outside the study area. Diagrams present (**A**) total VMAD of all rivers and (**B**) VMAD per river system in each impact class. Unaffected tributaries ≥100 m$^3$ s$^{-1}$ in affected large river systems are also indicated (Vindelälven in Sweden and Ounasjoki in Finland). Impact classes are defined in Table 5, and river system numbers refer to those in Table 2.

## Impact Class Distribution

To summarize our data on fragmentation of the river channel and flow regulation, we classified the river systems into three levels of impact: strongly affected, moderately affected, and not affected (*31*). Unaffected river systems are basically those without dams in their catchments, but dams in tributaries may not be disqualifying if flow regulation is <2% of the VMAD (Table 5). If there are dams in the main channel, the river system is never considered unaffected, and if there are no dams in the main channel, it is never classified as strongly affected. All river systems with less than one-quarter of their main channel length left without dams are considered strongly affected. The limit between the strongly and moderately affected classes was chosen primarily to enhance resolution (Table 5), whereas the unaffected class was conservatively defined from an ecological point of view.

Thirty-nine percent of the LRSs, representing 23% of the total VMAD (57,639 m$^3$ s$^{-1}$), are still unaffected by river channel fragmentation and flow regulation. There are 35 LRSs, with a total VMAD of 32,710 m$^3$ s$^{-1}$, left unaffected in North America, compared with 19 (24,929 m$^3$ s$^{-1}$) in Eurasia (Figs. 1 and 2). In terms of VMAD, the runoff from an average regulated and fragmented LRS is twice that of an unaffected one (2305 versus 1067 m$^3$ s$^{-1}$), and the largest unaffected river system, the Yukon, is only 11th in size or about one-third the size of the Yenisey (Table 4). On the other hand, four of the seven largest river systems are only moderately affected, and two of these have dams only in their tributaries. The third largest river of the study area, the Lena in Russia, has dams

**Table 4.** The class of impact (Table 5) and biogeographic diversity and setting (*28*) of all river systems with a VMAD of 5000 m$^3$ s$^{-1}$ or more (*14*, *15*) in the northern third of the world. The numbers beside river systems refer to those shown in Figs. 1 and 2. Abbreviations: NLF, temperate needle-leaf forests or woodlands; TG, temperate grasslands; BLF, temperate broadleaf forests or woodlands; MMH, mixed mountain and highland systems with complex zonation.

| River system | VMAD (m$^3$ s$^{-1}$) | Impact | No. of biomes | Dominating biome | No. of provinces | Dominating biogeographic province |
|---|---|---|---|---|---|---|
| 131. Yenisey | 20,000 | Strong | 5 | NLF | 6 | East Siberian taiga |
| 74. Mississippi | 18,400 | Strong | 4 | TG | 5 | Grasslands |
| 125. Lena | 16,900 | Moderate | 3 | NLF | 4 | East Siberian taiga |
| 135. Ob | 12,800 | Moderate | 4 | NLF | 6 | West Eurasian taiga |
| 116. Amur | 10,900 | Moderate | 3 | BLF | 4 | Manchu-Japanese mixed forest |
| 58. St. Lawrence | 10,800 | Strong | 3 | NLF | 3 | Canadian taiga |
| 21. Mackenzie | 9910 | Moderate | 3 | NLF | 4 | Canadian taiga |
| 112. Volga | 8050 | Strong | 4 | NLF | 5 | West Eurasian taiga |
| 4. Columbia | 7500 | Strong | 3 | MMH | 4 | Rocky Mountains |
| 106. Danube | 6450 | Strong | 3 | BLF | 5 | Middle European forest |
| 17. Yukon | 6370 | No | 3 | NLF | 3 | Yukon taiga |

only in one large (Vilyui) and one very small tributary.

The unaffected LRSs, with few exceptions, flow entirely within boreal and arctic regions (Figs. 1 and 2 and Table 3). Of the 17 largest unaffected river systems, only three have dominating biomes other than taiga and tundra: the Kamchatka River of eastern Russia, and the Skeena and Stikine rivers of western Canada (Table 6). All river systems that have parts of their catchments in deserts, semideserts, or lake systems (*32*) are strongly affected (Table 3). Furthermore, there is no free-flowing LRS with any part of its catchment in the temperate grasslands or the evergreen sclerophyllous biomes.

Among the 59 MRSs of Norway, Sweden, Finland, and Denmark, even fewer are left free-flowing: only 15% of the MRSs, representing 9% of the VMAD (Table 2 and Fig. 3). The average unaffected MRS is half the size of the average strongly affected one (67 versus 134 $m^3 s^{-1}$). All but one of the free-flowing MRSs have a VMAD of as little as 75 $m^3 s^{-1}$ or less. The Nordic MRSs show the same latitudinal gradient of exploitation (Fig. 3) as do the LRSs on the global scale. Some river systems in the north have remained unaffected, whereas southern river systems, especially in the temperate, broad-leaf biome, are strongly affected. Only two out of 18 river systems with VMADs larger than 40 $m^3 s^{-1}$ within this biome are moderately affected, namely, Tovdalsvassdraget and Bjerkreimsvassdraget, both in Norway, and none is free-flowing. Among the fragmented and regulated river systems, we found only two unaffected tributaries larger than 100 $m^3 s^{-1}$ (Fig. 3), both located in the north: Vindelälven (200 $m^3 s^{-1}$) in Sweden and Ounasjoki (140 $m^3 s^{-1}$) in Finland.

## Implications for Conservation Management

Large areas in the northern third of the world completely lack unregulated LRSs. Although river exploitation may have different effects in different rivers, some inevitable consequences stand out. For example, several types of important habitats, such as waterfalls, rapids, and floodplain wetlands, may disappear from entire regions. The loss of waterfalls and rapids indicates the loss of numerous species of plants and animals specific to running waters. Wetland losses are especially serious in dry areas where alternative habitats are scarce. As a result of habitat destruction and obstruction to organism dispersal, many riverine species may have become extinct over vast areas, whereas populations of others have become fragmented and run the risk of future extinctions. Although regional depletion of river faunas has been demonstrated and habitat fragmentation by dams has been shown to be a major cause of this depletion (*33*), there is insufficient knowledge of the general stage of this depletion. The final result of the present exploitation is also difficult to predict because the time needed for reequilibration of ecosystems is probably longer than the time river regulation has been in practice (*2, 34*).

Would a higher resolution of river conditions change this conclusion? For example, it is not certain that an LRS classified as strongly impacted is so in every part of its catchment. However, low contribution of reasonably large, unaffected tributaries in affected river systems in Norway, Sweden, Finland, and Denmark suggests that such remaining parts are generally small. The largest strongly affected river systems in the study (Table 4) might have large, unaffected tributaries or parts of tributaries. However, these are not complete rivers because they have no direct connections with the sea; they therefore lack, for example, estuarine flora and fauna.

River systems smaller than those we considered are also unlikely to match the losses in regional ecosystem diversity that have befallen the LRSs. Small rivers have a species composition different from that of large rivers (*25, 35*), and as suggested by the study of Norway, Sweden, Finland, and Denmark, MRSs may show the same geographic pattern of human impact as do LRSs.

To improve the conservation of biodiversity and the sustainable use of biological resources, immediate action is required (*36*). River conservation efforts should be based on the main tenet of the World Con-

**Table 5.** 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. The fragmentation classes are defined in Table 1. Summed values of reservoir live storages, interbasin diversions (irrespective of direction) and irrigation consumption are given as the percentage of VMAD (Table 1). If data on live storage are lacking, half the gross capacity is used as a substitute (Table 1).

| 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 |

**Table 6.** The biogeographic diversity and setting (*28*) of all free-flowing river systems with a VMAD of 1000 $m^3 s^{-1}$ or more in the northern third of the world. The numbers by the river systems refer to those in Figs. 1 and 2. Abbreviations: NLF, temperate needle-leaf forests or woodlands; TUN, tundra communities and barren arctic desert; BLFn, northern temperate broad-leaf forests or woodlands as described in Table 3; MMH, mixed mountain and highland systems with complex zonation.

| River system | VMAD ($m^3 s^{-1}$) | No. of biomes | Dominating biome | No. of provinces | Dominating biogeographic province |
|---|---|---|---|---|---|
| 17. Yukon | 6370 | 3 | NLF | 3 | Yukon taiga |
| 136. Pechora | 4100 | 2 | NLF | 2 | West Eurasian taiga |
| 128. Khatanga | 3200 | 2 | NLF | 2 | East Siberian taiga |
| 130. Pyasina | 2260 | 2 | TUN | 3 | Low-Arctic tundra |
| 121. Anadyr | 2020 | 2 | TUN | 3 | Low-Arctic tundra |
| 16. Kuskokwim | 1900 | 2 | NLF | 2 | Yukon taiga |
| 7. Skeena | 1760 | 2 | MMH | 2 | Rocky Mountains |
| 12. Copper | 1700 | 2 | NLF | 2 | Yukon taiga |
| 123. Indigirka | 1700 | 2 | NLF | 3 | East Siberian taiga |
| 9. Stikine | 1600 | 2 | MMH | 2 | Rocky Mountains |
| 132. Taz | 1540 | 1 | NLF | 1 | West Eurasian taiga |
| 13. Susitna | 1400 | 1 | NLF | 1 | Yukon taiga |
| 24. Thelon, Kazan | 1370 | 2 | TUN | 2 | Canadian tundra |
| 126. Olenek | 1090 | 2 | NLF | 3 | East Siberian taiga |
| 120. Kamchatka | 1050 | 1 | BLFn | 1 | Kamchatkan |
| 133. Pur | 1050 | 2 | NLF | 2 | West Eurasian taiga |
| 15. Nushagak | 1000 | 2 | TUN | 2 | Alaskan tundra |

servation Strategy: the maintenance of ecological processes (*11*). Water flow and water-level fluctuation are most important because various other processes depend on them (*8, 37*). To maintain a near-natural water transport through the landscape, we should not limit our scope to the river channel but should include the entire catchment (*38*). For example, the ability of the catchment to dampen large natural fluctuations in rainfall and snowmelt must not be reduced. Today, naturally regulated runoff patterns in the catchment are being indirectly deregulated, especially by embankments, draining, and deforestation but also by urbanization and industry (*39*).

Different challenges are faced in different biomes. In the northern world's tundra and taiga biomes as well as in the temperate rain forest areas of Alaska and Canada, it is still possible to create an international preservation network of representative, unregulated, and unfragmented LRSs. Unless an entire catchment can be protected in one large reserve, a network of reserves is necessary to protect its entire range of biotic diversity (*40*). In the other biomes, the magnitude of impact indicates that river channel fragmentation and water regulation have had profound ecological effects on the LRSs (*2, 5–7*). Here, legislation forbidding dams on remaining free-flowing tributaries and main-channel reaches is a minor tool. More important is to find ways to minimize the negative effects of existing dams and diversions and also to consider the pervasive influences of pollution, riparian logging and agriculture, poor land-use practices within the catchment, and the invasion or introduction of nonnative biota (*41*). All of these influences fragment and otherwise compromise natural attributes and processes in river ecosystems and add to the effects of dams and diversions. Fully integrated catchment management, including measures of ecological rehabilitation, is needed (*20, 42, 43*).

Ecological rehabilitation of degraded river systems may include a variety of measures. For example, the rehabilitation of channel sinuosity will increase the retention of matter and energy (*44*). The rehabilitation of naturally functioning floodplains is essential to provide wildlife habitat and help reduce or buffer non–point-source pollution (*45*). This change necessitates both the reconnection of the river with its floodplains and the modification of water-level fluctuations toward more natural conditions (*46*). Examples of ongoing projects exist along the Danube and Rhine rivers in Germany and along the Mississippi River in the United States (*47*). The rehabilitation of migration routes and spawning sites is essential to recover anadromous salmonids; such work is under way in the Columbia River, for example (*42*). In some cases, the removal of dams is also considered, as for the Elwah River of the Olympic Peninsula in the state of Washington, United States, where authorities are considering tearing down two dams, 30 and 70 m high (*48*). River rehabilitation measures must be based on a synthesis of ecological principles and include a basic research component to allow an adaptive refinement of management objectives as new information becomes available (*49*).

So far, river conservation management has mainly been a national concern. For example, legislations and plans to preserve rivers have been introduced in the United States, Canada, Norway, Sweden, and Finland (*50*). In this way, the main channels of the Seal, Thelon, and Kazan, the major part of the Alsek and Noatak rivers (all in North America), and the entire river system of Torne-Kalix (in Fennoscandia) have been protected. In addition, many minor parts of other LRSs are protected, and in some cases national borders also form boundaries of protection, as for the Alsek River of Alaska and western Canada (protected only in Canada) and for Vefsna, an MRS shared by Sweden and Norway (protected only in Sweden). Time has now come to adopt an international approach to river conservation and manage entire river systems irrespective of political borders.

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24. The definition indicates that two rivers with significant connections of natural surface freshwater through river-mouth deltas or through upstream natural cross-channels, so-called bifurcations, comprise one river system. This definition is ecologically reasonable because freshwater organisms can migrate between such rivers. Examples are the Torne-Kalix river system in Sweden and Finland, the Rhine-Maas river system in northwestern continental Europe, and the Sacramento-San Joaquin river system of California. Tributaries are not regarded as complete river systems because they have no connection to the sea.
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