DEVELOPMENT AND ENVIRONMENT

Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong

Basin-scale planning is needed to minimize impacts in mega-diverse rivers

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POLICY

The world's most biodiverse river basins—the Amazon, Congo, and Mekong—are experiencing an unprecedented boom in construction of hydropower dams. These projects address important energy needs, but advocates often overestimate economic benefits and underestimate far-reaching effects on biodiversity and critically important fisheries. Powerful new analytical tools and high-resolution environmental data can clarify trade-offs between engineering and environmental goals and can enable governments and funding institutions to compare alternative sites for dam building. Current site-specific assessment protocols largely ignore cumulative impacts on hydrology and ecosystem services as ever more dams are constructed within a watershed (*1*). To achieve true sustainability, assessments of new projects must go beyond local impacts by accounting for synergies with existing dams, as well as land cover changes and likely climatic shifts (*2*, *3*). We call for more sophisticated and holistic hydropower planning, including validation of technologies intended to mitigate environmental impacts. Should anything less be required when tampering with the world's great river ecosystems?

ONE-THIRD OF FRESHWATER FISH AT RISK. The Amazon, Congo, and Mekong basins hold roughly one-third of the world's freshwater fish species, most of which are not found elsewhere. Each of these rivers has experienced limited hydropower development to date, largely because their vast catchments had limited infrastructure and low energy demand. Most existing dams are relatively small and located in upland tributaries, but more than 450 additional dams are planned for these three rivers alone (see the chart), with many already under construction (*4*). Dams are usually built where rapids and waterfalls boost hydropower potential. Unfortunately, these high-gradient reaches are home to many unique fishes adapted for life in fast water (fig. S1).

Although available data on geographic distributions of tropical fishes and other aquatic taxa are incomplete, recent research within these great river basins makes it clear that dam site selection matters greatly for conserving biodiversity (*5*) (see the chart). Given recent escalation of hydropower development in the tropics (*4*), planning is needed at the basin scale to minimize biodiversity loss, as well as other environmental, social, and economic effects (*3*, *6*–*9*). Large dams invariably reduce fish diversity but also block movements that connect populations and enable migratory species to complete their life cycles. This may be particularly devastating to tropical river fisheries, where many high-value species migrate hundreds of kilometers in response to seasonal flood pulses (*8*–*12*). Model simulations of proposed dams in the lower Mekong Basin predict major reductions of migratory stocks (*8*), as has been widely observed globally (*11*). Fish passages constructed to mitigate dam impacts on migratory fishes in the neotropics have proven unsuccessful (*10*) and even harmful (*12*). Yet, dam proposals continue to tout fish passages as the principal means for minimizing impacts on migratory stocks.

> *"[D]am site selection matters greatly for conserving biodiversity."*

Large dams delay and attenuate seasonal flood pulses, reducing fish access to floodplain habitats that are essential nursery areas and feeding grounds. Physical alterations bring about an ecological regime shift, whereby a dynamic system with high structural and functional complexity becomes relatively homogeneous and less productive. Tropical reservoir fisheries are often dominated by low-value species plus a few nonindigenous species introduced for recreational angling or aquaculture (*13*). Ecological effects of large dams are not limited to rivers; trapping sediment alters nutrient dynamics and other biogeochemical processes in deltas, estuaries, and marine-shelf ecosystems, which in turn impact agriculture, fisheries, and human settlements (*14*).

A lack of transparency during dam approval processes has raised questions about whether funders and the public are fully informed about risks and long-term impacts on tropical river systems that support livelihoods of millions of people (*3*). Some tropical developing countries lack protocols guiding construction of hydroelectric dams, and many countries exempt small dams (<10 MW) from any formal decision-making process. Even when environmental impact assessments are mandated, millions of dollars may be spent on studies that have no actual influence on design parameters, sometimes because they are completed after construction is under way.

Planners have generally failed to assess the true benefits and costs of large hydropower projects. Returns have usually fallen short of expectations even without adjustment for risk, and an estimated 75% of large dams suffered cost overruns that averaged 96% above the figures used to justify their creation (*15*). Economic projections frequently exclude or underestimate the costs of environmental mitigation, as in the case of the ~$26 billion spent by China to moderate ecological impacts of the Three Gorges Dam (*16*).

Hydropower accounts for more than two-thirds of Brazil's energy supply, and at least 334 new Amazon dams have been proposed (*4*). Impacts of these dams would extend well beyond direct effects on rivers to include forced relocation of human populations and expanding deforestation associated with new roads (*4*). Scheduled for completion in 2016, Brazil's Belo Monte hydropower complex was designed with installed capacity of 11,233 MW, ranking it the

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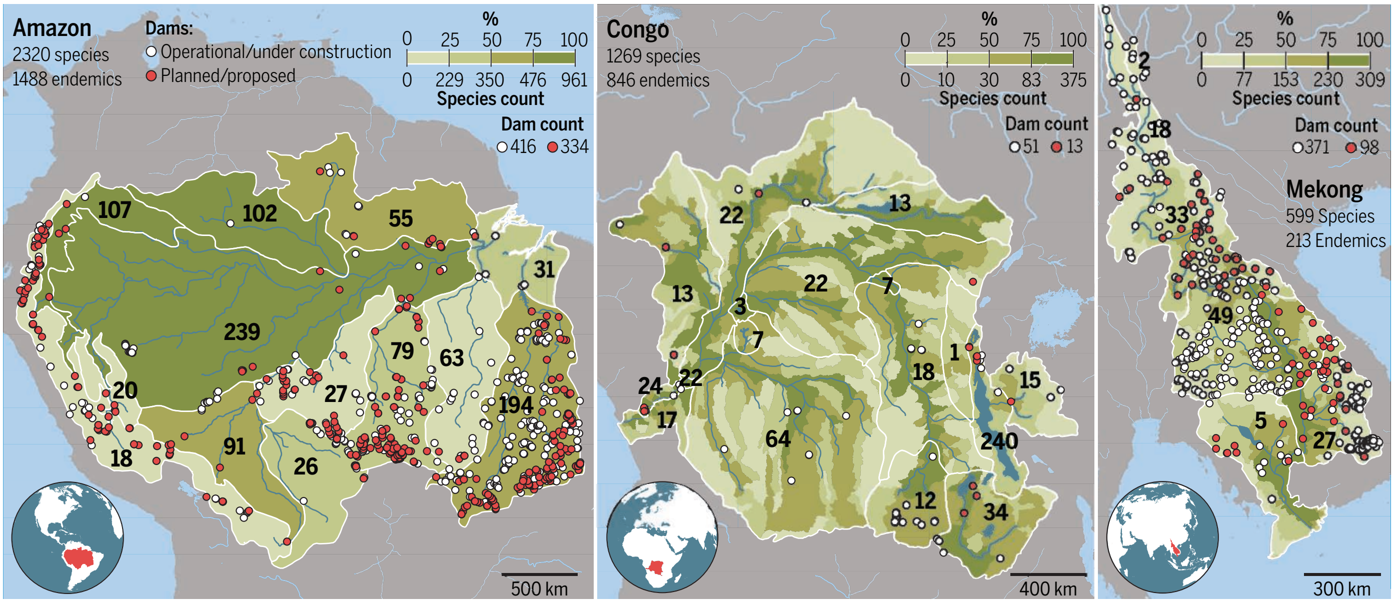

Fish diversity and dam locations in the Amazon, Congo, and Mekong basins. In addition to basin-wide biodiversity summaries (upper left in first two panels, middle in third panel), each basin can be divided into ecoregions (white boundaries). Many species are found only in a single ecoregion (black numbers), and subbasins within each river basin differ widely in their total species richness (shades of green illustrate breakpoints between quartiles in rank order within each basin). Dozens of new taxa are discovered every year in each basin; hence, actual fish diversity is underestimated, and distribution data are lacking for many species. Nonetheless, fish diversity data are now sufficient to support basin-scale impact assessments. See SM for data and methods.

IMAGE: WINEMILLER *ET AL.* ADAPTED BY P. HUEY/*SCIENCE*

world's third largest. Actual power generation, however, is expected to be much lower. Belo Monte may set a record for biodiversity loss owing to selection of a site with exceptional species endemism (*5*).

The Congo has far fewer dams than the Amazon or Mekong (see the chart), yet most power generated within the basin is from hydropower. Inga Falls, a 14.5-km stretch of the lower Congo that drops 96 m to near sea level, has greater hydropower potential than anywhere else (*6*). The Inga I and II dams, constructed in the 1970s and 1980s, currently yield 40% of the 2132-MW installed capacity (*6*). Planned additional dams (Inga III and Grand Inga) would harness as much as 83% of the Congo's annual discharge, with most of the energy to be exported (*6*). Grand Inga would divert water and substantially reduce flow for at least 20 km downstream from the falls.

Six large dams have been built on the upper Mekong since the mid-1990s, and there are plans for at least 11 more on the middle and lower reaches. Rural communities in the lower basin rely on harvesting wild fish species whose longitudinal migrations would be profoundly disrupted by dams on the mainstem or even major tributaries (*7*–*9*). For instance, damming the Mun River in Thailand has had a wide range of detrimental social and economic impacts (*7*). Maintaining regional food security in the face of projected fishery losses arising from 88 new dams planned for the basin by 2030 would require a 19 to 63% expansion of agricultural land (*9*).

RECOMMENDATIONS. Long-term ripple effects on ecosystem services and biodiversity are rarely weighed appropriately during dam planning in the tropics. We are skeptical that rural communities in the Amazon, Congo, and Mekong basins will experience benefits of energy supply and job creation that exceed costs of lost fisheries, agriculture, and property. An improved approach to dam evaluation and siting is imperative.

Integrative, strategic planning must be applied at the basin scale, with the goal of finding balance between tapping hydropower potential and sustaining key natural resources. Spatial data on biodiversity and ecosystem services are increasingly available to support sophisticated trade-off analyses [see supplementary material (SM)]. New analytical methods can account for cumulative impacts from multiple dams to hydrology, sediment dynamics, ecosystem productivity, biodiversity, fisheries, and rural livelihoods throughout watersheds (*1*, *17*–*19*). Incorporating these data and tools into assessment protocols would boost the credibility of dam siting to stakeholders.

Institutions that permit and finance hydropower development should require basin-scale analyses that account for cumulative impacts and climate change. Proposed dam sites must be evaluated within the context of sustaining a portfolio of ecosystem services and biodiversity conservation, and alternative sites should be considered explicitly. Such common-sense adjustments to assessment procedures would ensure that societal objectives for energy production are met while avoiding the most environmentally damaging projects. Without more careful planning, species extinctions and basin-wide declines in fisheries and other ecosystem services are certain to accompany new hydropower in the world's mega-diverse tropical rivers. ■

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SUPPLEMENTARY MATERIALS

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