

Village fishermen exploit the predictable bounty of the annual flood in the Lower Mekong Basin.



PERSPECTIVES

INFRASTRUCTURE

Can dams be designed for sustainability?

Dam design on the Mekong River can help to support water, energy, and fisheries needs

By **N. LeRoy Poff**^{1,2} and **Julian D. Olden**^{3,4}

Water, food, and energy security are cornerstones of a sustainable and prosperous future. Rivers play a key role in delivering critical ecosystem services that contribute to this security on a global scale. But decisions concerning how rivers are harnessed or otherwise used for the benefit of human societies inevitably create environmental and social conflicts, particularly when new dams threaten valued ecosystem services. Given the proposed proliferation of thousands of new dams in many developing countries (1), can policy-makers and managers be smarter in dam design and operation to reduce these inherent conflicts to generate valuable co-benefits? On page 1270 of this issue, Sabo *et al.* (2) propose a novel approach to designing flow releases from existing and proposed dams in the Mekong River Basin in order to sustain a highly valued and threatened natural fishery.

In Southeast Asia, the Mekong River and its tributaries support a natural floodplain fishery that ~60 million people rely on di-

rectly for their sustenance and livelihoods. Six upstream dams currently exist on the Mekong River, and another 13 are planned to provide hydroelectric energy and stored irrigation water for the people of China, Cambodia, and Laos. Operation of existing dams and construction of new dams pose a great risk to the region's sustainable fisheries, both by erecting migration barriers for spawning fish and by altering the seasonal cycle of flooding and draining of the vast lowland areas required to support fish production (3). Can dams, which inevitably alter natural river hydrology, be operated or designed to meet the fishery's hydrological needs?

To answer this question, Sabo *et al.* analyzed more than a decade of annual fisheries catch in the Tonle Sap River-floodplain complex of Cambodia, a key source of fish production in the lower Mekong. Using spectral analysis techniques, they identified dominant signals in the hydrology time series that best explain interannual variation in fish harvest. On the basis of the resulting fish-hydrology relationships, they propose an engineered flow regime for the Tonle Sap that reflects elements of the historical, pre-dam flow regime in the basin, but with some key differences. Seasonal floodplain drying would be prolonged, followed by a very rapid transition to seasonal flooding. The authors find that the statistically optimized designer flow regime would lead to a

two- to fourfold increase in fisheries catch compared with the historical (pre-dam) natural flow regime. The water volumes needed to create the seasonally timed designer flow already exist in upstream water storage dams. New dams could be operated to contribute to the designer flow.

Considerable political motivation would be required to coordinate the multinational interests in the Mekong Basin to manage toward such a designed flow regime. Nonetheless, Sabo *et al.*'s study illustrates how dams can be operated to improve an essential fishery for millions of people while also providing energy and water security needs. Sabo *et al.*'s model approach is, in principle, transferable to other river basins where similar threats to sustainable fisheries are posed, such as the Amazon River Basin, which is also slated for extensive hydropower dam expansion (4, 5).

As conflict over water resources increases under growing population demands and accelerating climatic change, designing flows in dam-regulated rivers to meet both human consumption needs and valued ecosystem functions will become more pressing (6). The world's rivers are extensively modified by tens of thousands of dams (7), resulting in many lost ecosystem services, including native fisheries (8). Strategic flow releases from dams to maintain or restore degraded ecosystem functions and ecological targets are now receiving greater attention from river

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scientists and managers (9, 10), and these can potentially be balanced with human demands. For example, in drought-prone rivers, flows can be designed to favor native over non-native fish species while simultaneously meeting human water needs (11).

The Sabo *et al.* paper reinforces the growing understanding that water managers can, and must, balance socioeconomic and ecological needs for regulated rivers. Incorporating flexibility into the design of new dams will enable proactive maintenance of downstream ecosystem services, even as future hydrology and social demands for water change (6). Such flexibility will be critical for adaptive management; it should be mandated for all new dam constructions and selectively required for existing dams.

With the likely expansion of the designer flow philosophy, careful evaluation of limitations and uncertainties is needed. For example, Sabo *et al.*'s work shows that production of key species in the Tonle Sap fishery is likely to be enhanced under a designed flow regime; however, it remains unclear whether such engineered flows support broader biodiversity that may promote sustainable fish populations.

Ultimately, managing rivers for multiple, sustainable benefits requires integrating scientific, social, and policy perspectives into operational decision frameworks (12). In rivers, optimizing among divergent stakeholder interests remains a challenge because flow-dependent benefits are distributed in complicated and often unspecified ways (13). For example, the water-dependent cultural values of local or indigenous peoples have historically been largely excluded from water management decisions and are therefore often deemphasized in decisions about building and operating water infrastructure (14). In the Mekong River, cultural values and economic livelihoods align around the native fisheries. Given this, Sabo *et al.*'s work is an exemplar of how ecological science can inform equitable distribution of river-dependent benefits toward achieving social-ecological sustainability in complex and contested river ecosystems. ■

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BIOCHEMISTRY

Putting the RuBisCO pieces together

Scientists find a way to build the major plant enzyme RuBisCO in bacteria

By **Todd O. Yeates** and **Nicole M. Wheatley**

Among the thousands of different enzymes that have evolved in nature, ribulose-1,5-bisphosphate carboxylase-oxygenase (known as RuBisCO) holds a special place. It is the enzyme in plants, algae, and many photosynthetic bacteria that ultimately takes energy derived from the Sun and uses it to convert or “fix” atmospheric CO₂ into organic forms of carbon that constitute the basis for life (1). Globally, RuBisCO fixes enormous quantities (gigatons) of carbon annually. To carry out such a massive chemical conversion requires a huge amount of the enzyme, especially because RuBisCO performs reactions quite slowly. Accordingly, RuBisCO is believed to be

“Can plant RuBisCO be engineered more easily now to make an improved enzyme for agricultural use?”

the most abundant enzyme on the planet (1, 2). RuBisCO is unusual in other ways as well. Each RuBisCO enzyme in the cell requires a tremendous amount of help, from chaperones, to fold into the correct three-dimensional shape required for its function. The large number of chaperones is important for two reasons. One is that there are numerous questions about the identities of these chaperones and how they operate on a structural level. Another is that it has been difficult to produce correctly folded RuBisCO in laboratory experiments, which has also limited the ability to engineer alternate forms of the enzyme. On page 1272 of this issue, Aigner *et al.* (3) fill in some of the most important remaining pieces of the RuBisCO folding and assembly puzzle.

The amino acid sequence of a protein encodes the final three-dimensional structure

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into which it folds. But to fold correctly, some proteins require help from chaperones (4, 5). Intriguingly, most cellular proteins that need help folding get by with the assistance of one or a few generic chaperones that fold many different proteins, whereas RuBisCO requires numerous chaperones, including some that appear dedicated exclusively to that special task (6–10). The task is made more complex by the need to assemble 16 total protein subunits together (L₈S₈, eight large and eight small subunits) in one RuBisCO enzyme.

Aigner *et al.* found that seven chaperones—chaperonin 60-subunit α1 (Cpn60α), Cpn60β, 20-kDa chaperonin (Cpn20), RuBisCO assembly factor 1 (RAF1), RAF2, ribulose bisphosphate carboxylase factor X (RbcX), and bundle-sheath defective-2 (BSD2)—help plant RuBisCO fold and assemble when the proteins are all expressed together in the bacterium *Escherichia coli* (see the figure). The Cpn60α–Cpn60β chaperone complex provided for general adenosine 5′-triphosphate-dependent protein folding of the large subunit of RuBisCO. The Cpn60 complex forms a large, barrel-shaped structure and is assisted by small capping subunits, Cpn10 or Cpn20. Misfolded proteins are drawn into the Cpn60 barrel interior where they can be refolded within a protected environment. Consistent with previous reports (11, 12), the authors found that two slightly different versions of Cpn60—Cpn60α and Cpn60β—are required in combination for plant RuBisCO large-subunit folding, and they cannot be replaced by their homolog in *E. coli*, GroEL. This is in contrast to cyanobacterial chaperonins, which can be substituted by GroEL to fold cyanobacterial RuBisCO.

Although the general Cpn60–Cpn20 chaperone complex can fold RuBisCO large subunits, more specialized chaperones are needed to assemble RuBisCO into its final L₈S₈ form. Aigner *et al.* clarify the role of all four of the known plant RuBisCO-specific chaperones: RbcX, RAF1, RAF2, and BSD2. Previous studies showed that RbcX (6) and RAF1 (7) both bind and stabilize pairs of RuBisCO large subunits during the multistep assembly process, suggesting that they might be functionally redundant. But, Aigner *et al.* show that RbcX cannot effectively replace

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