The use of tailored supramolecular structures for PV applications allows the study of the fundamental physics and chemistry of nanostructured materials through unraveling structure-property relations. The vertical-channel device configuration can be exploited for model studies in spintronics and other applications in optoelectronics such as light-emitting diodes and transistors, which require the optimal combination of asymmetric electrodes with ad hoc work function, nanoscale controlled channel length, and maximal density of active nanostructures. Photovoltaic performance could also be optimized by using SMNWs with higher charge mobility or by introducing a dopant to improve conductivity (*9, 10*). In addition, the gold nanomesh could enhance optical absorption by acting as a plasmonic antenna (*11*), increasing quantum efficiency. The photoresponse could be used to develop ultrafast nanoscale photodetectors, which would be components of future optical quantum computers. Alternative lithographic methods, such as nanoimprint or nanostencil (*12, 13*), could access more complex geometries that are required for specific architectures (such as memory storage devices).

Controlling supramolecular interactions holds the promise of growing highly ordered organic films and nanostructures, which is a prerequisite for the fabrication of high-performance devices (*14*). The device configuration of Zhang *et al.* bridges the gap between bottom-up grown semiconductor nanostructures and macroscopic photonic technologies. We anticipate that it will draw broad interest from the scientific community and affect future developments at the intersection between supramolecular chemistry, nanotechnology, and optoelectronics. ■


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ECOLOGY

# How dams can go with the flow

## Small changes to water flow regimes from dams can help to restore river ecosystems


*By* **N. LeRoy Poff**[1,2] *and* **John C. Schmidt**[3]


The world's rivers are regulated by about 58,000 large dams (more than 15 m high) that provide water supplies for municipalities and irrigation, allow downstream navigation, and enable hydropower production (*1*). New dams are widely seen as sources of green energy. An estimated 75% of the world's potential hydropower capacity is unexploited (*2*), and some 3700 new dams are currently proposed in developing economies (*3*, *4*).

***"Managing...rivers to better meet both human and ecosystem needs is a complex societal challenge."***

But dams also cause substantial and often unacknowledged environmental damage. Recent research affords insight into how dams might be strategically operated to partially restore some lost ecosystem functions and services.

Dams transform rivers by creating artificial lakes, fragmenting river networks, and greatly distorting natural patterns of sediment transport and of seasonal variation in water temperature and stream flow (*5*). Impeded upstream-downstream movement of fish and other species and highly altered environmental conditions severely impair downstream ecosystems by modifying productivity and causing species extirpations and replacements (see the figure). Intentional releases of reservoir water can restore some semblance of the predam flow regime. Such environmental flows (*6*) enable recovery of some lost ecosystem functions but carry an economic cost by a dam's operational efficiency.

Many hydropower dams release more water during daytime when societal demand for electricity is greatest. Such hydropeaking creates a fluctuating daily pattern of water flows that typically severely impairs productive, downstream shoreline habitats through repeated wetting and drying. River scientists have long struggled with the conundrum of how to diminish these negative ecological effects in a cost-effective manner, given the strong economic incentive of hydropeaking. A recent study of the Colorado River ecosystem downstream from the hydropeaking Glen Canyon Dam by Kennedy *et al.* (*7*) offers a promising approach (see the figure).

The authors found that the river food web, a fundamental feature of a river's ecological integrity (*8*), lacks large aquatic insects, key species that are common in sections of the Colorado River not strongly influenced by hydropeaking flows. Although aquatic insects spend most of their lifetimes in the water, adults take flight to mate and lay eggs in shallow water near the shoreline. Large aquatic insects firmly cement their eggs just under the water surface on partially exposed boulders. Sudden drops in water level from hydropeaking expose them to the atmosphere and cause extensive mortality.

Using a model that estimates shoreline water-level fluctuations due to hydropeaking throughout the 400 km of river in the Grand Canyon, the authors evaluated egg desiccation risk based on female egg-laying behavior relative to fluctuating water levels. The model predicted that large insects would not occur anywhere in the Grand Canyon. But it also made a second, unexpected prediction: Native, small-bodied insect species would be much more common in two sections of the river where low water levels from the propagating hydropeaking waves occur predictably in the evening, when adults actively fly and lay eggs. These insect species do not cement all eggs on boulders, so some should remain underwater during the entire hydropeaking cycle and thus survive and hatch.

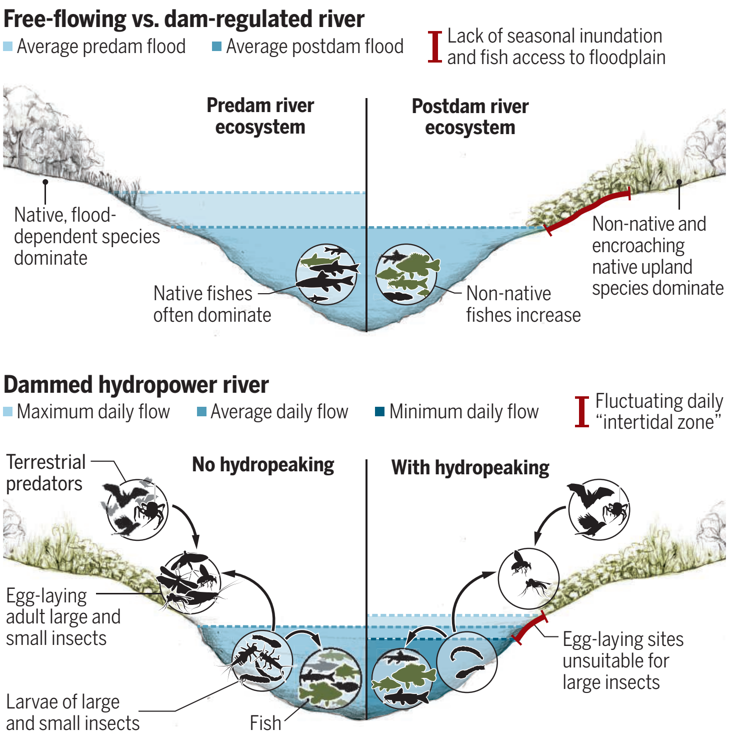
To test these predictions, the researchers turned to the river rafters who camp everywhere throughout the Grand Canyon from late spring to early fall. Over the course of 3 years, hundreds of these citizen scientists captured and preserved more than 2500 individual insect samples during 1 hour beginning at local sunset by attracting flying insects to ultraviolet lamps. The results were striking: Large-bodied insect species were


[1]Department of Biology, Colorado State University, Fort Collins, CO 80524, USA. [2]Institute of Applied Ecology, University of Canberra, ACT 2617, Australia. [3]Department of Watershed Sciences, Utah State University, Logan, UT 84322, USA. Email: n.poff@colostate.edu

rarely collected, and the small insects were more than three times as abundant in the two places predicted by the model. Comparing their data with that from studies on 15 other dammed rivers in the western United States, Kennedy *et al.* show that aquatic insect diversity is lowest where hydropeaking is greatest (*7*).

## How dams affect river ecosystems

Dams alter flow, sediment, and thermal regimes of rivers. Seasonal flow distortions (top) cause shifts in species compositions. Dammed rivers with hydropeaking (bottom) cause daily distortions that can eliminate key species from food webs. Small changes to flow releases can counteract these distortions and provide ecological benefit (see text).




Based on their results, Kennedy *et al.* propose an experiment as part of the Long-Term Experimental and Management Plan for Glen Canyon Dam. Eliminating hydropeaking on weekends, when energy demand is relatively low, would make reliable egg-laying habitat available. Restricting hydropeaking on several weekends each year during the prime reproductive season might suffice to allow the highly fecund aquatic insects to recover in abundance within a few years. Restoring the integrity of the food web with large insects should enhance production of river fishes and also benefit terrestrial predators that eat flying adult insects (birds, bats, and spiders) at minimal cost to foregone hydroelectric production.

The principle of targeted, cost-effective flow restoration is also emerging from research on dams that distort the natural patterns of seasonal, rather than daily, flows. For most large dams, runoff from spring rains or snowmelt is stored in the reservoir to be released later in the year for hydropower, water supply, or irrigation. Environmental flow restoration in these rivers often aims to recreate a large, seasonal flow pulse timed to meet downstream ecosystem needs (such as floodplain inundation for riparian vegetation or stimulation of fish spawning or migration). At least 113 experimental flow releases have been conducted in more than 20 countries around the world with varying success (*9*). For these seasonally impaired rivers, a fundamental question is how a natural (seasonal) flow regime might be adequately mimicked to restore desired ecosystem functions but still adequately satisfy the utilitarian objectives of river regulation.

A study by Kiernan *et al.* shows how, as in the case of daily flows, seasonal flow regulation can help to restore ecosystem functions at low cost (*10*). The authors reported on nearly two decades of research conducted along a 30-km stretch of Putah Creek in California. An upstream dam diverts water for irrigation, reducing in-stream flows and facilitating the displacement of native fish species by exotic fishes. In an effort to reverse this trend, which is common in dammed rivers (see the figure), a court-ordered flow regime designed to benefit native species was implemented. High springtime flow pulses created favorable spawning and rearing conditions, and stable base flow releases maintained favorable flow conditions. After 9 years of flow management, native fishes had regained dominance in two-thirds of the study reach. Only a small annual increase in downstream water releases was needed, making this a cost-effective management strategy.

Managing the world's regulated rivers to better meet both human and ecosystem needs is a complex societal challenge. Opportunities to modify flow release patterns at existing dams are often constrained by original engineering design, but small changes to existing dam operations may be possible through incentives offered by regulatory relicensing requirements (*11*) and government dictates to incorporate consideration of ecosystem services in infrastructure management where possible (*12*). The studies by Kennedy *et al.* (*7*) and Kiernan *et al.* (*10*) show that even small operational tweaks have the potential to be ecologically beneficial.

The thousands of proposed new hydropower dams pose a significant global threat to freshwater biodiversity (*3*, *4*) and to the livelihoods of indigenous peoples who rely on ecosystem services of free-flowing rivers and floodplains (*13*). The conversion of free-flowing rivers to artificial lakes will fragment river corridors and diminish ecosystem services. Strategic planning is needed to decide where these dams can be located to lessen overall environmental and societal harm (*4*, *14*). Ideally, new dams should be designed to minimize distortions in flow and thermal regimes, allow sediment transport to downstream ecosystems, and enable fish migration throughout the river network.

Postdam environmental flow management can only incrementally improve lost ecosystem functions, making predam environmental planning essential. Making hydropower greener and dams more sustainable generally requires not only better design and management of flow releases but also balancing economic gain against environmental degradation and human dislocations, all in an increasingly uncertain hydrologic future (*15*). ■

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N. LeRoy Poff and John C. Schmidt

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