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Spatial design principles for sustainable hydropower development in river basins

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ABSTRACT

What is the best way to arrange dams within river basins to benefit society? Recent interest in this question has grown in response to the worldwide trend toward developing hydropower as a source of renewable energy in Asia and South America, and the movement toward removing unnecessary dams in the US. Environmental and energy sustainability are important practical concerns, and yet river development has rarely been planned with the goal of providing society with a portfolio of ecosystem services into the future. We organized a review and synthesis of the growing research in sustainable river basin design around four spatial decisions: *Is it better to build fewer mainstem dams or more tributary dams? Should dams be clustered or distributed among distant subbasins? Where should dams be placed along a river? At what spatial scale should decisions be made?* The following design principles for increasing ecological sustainability emerged from our review: (i) concentrate dams within a subset of tributary watersheds and avoid downstream mainstems of rivers, (ii) disperse freshwater reserves among the remaining tributary catchments, (iii) ensure that habitat provided between dams will support reproduction and retain offspring, and (iv) formulate spatial decision problems at the scale of large river basins. Based on our review, we discuss trade-offs between hydropower and ecological objectives when planning river basin development. We hope that future testing and refinement of principles extracted from our review will define a path toward sustainable river basin design.

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Contents

1. River portfolios

Dams now regulate more than half of large river systems in the world [1]. During the 20th century, around 80,000 hydroelectric dams were constructed in the US, including 137 very large dams [2], and by 1990, fewer than 42 free-flowing sections of

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river over 125 miles in length existed and the remaining 98% of US streams were fragmented by dams and water diversions [3]. Obsolete non-power dams and some power dams have been removed for a variety of reasons [2]. Development of new hydropower is now accelerating in Southeast Asia, Africa, and Latin America. Hydropower is the world's leading form of market-based renewable energy. In 2012, hydropower provided 76% of renewable energy and 6% of electricity overall worldwide [4].

In addition to energy, society relies on rivers to provide a range of ecosystem services including clean water, fisheries, and recreation. To support these diverse objectives, scientists and decision makers are looking for tools to guide the development and management of rivers in a sustainable direction with the goal of maximizing ecosystem services provided to society over the long term [5]. Rivers can be viewed as a portfolio of assets with dynamic value and risks that require management [6]. The Millennium Ecosystem Assessment [7] (MEA) identified four classes of ecosystem services that can apply to rivers. These include *provisioning* (e.g., energy, clean water, fish), *regulating* (e.g., filtration, nutrient cycling), *cultural* (e.g., recreational fishing), and *supporting* (e.g., primary production, biodiversity) ecosystem services. In this paper, we focus on hydropower (a *provisioning* ecosystem service) and *supporting* services derived from biodiversity in healthy river ecosystems. If we wish to derive ecosystem services from rivers in the future, we might think about managing river portfolios by setting investment goals, valuing assets, and reducing exposure to risk.

Hydropower development shifts the ecosystem services that river portfolios provide to society. As provisioning services like hydropower increase, other ecosystem services typically decline [8], and this trend has continued over time [7]. Perhaps more than hydropower development per se, damming rivers decrease other ecosystem services [9–11]. Freshwater taxa have declined at a faster rate than taxa in any other type of ecosystem [12], and impoundment by dams has contributed to this decline.

The effects of impoundment and hydropower are often confounded. Water storage is generally the driver for building dams and reservoirs. Arguably, power generation is neither the primary reason for impoundment nor the primary driver for species declines typically associated with dams. The potential for generating hydrokinetic energy without dams ("dam-free hydro") has promise as a means of minimizing environmental costs (see Box 1). However, the majority of hydropower comes from projects with complete dams and the spatial optimization studies reviewed here focused on hydropower associated with dams.

Box 1–Damless hydropower.

Although economic feasibility is an issue (energy produced from high-head dams is more cost-effective and capital equipment is expensive [59]), low-head, damless hydrokinetic projects offer two distinct advantages relative to larger projects at dams: (1) high social sustainability through decentralized access to power in rural areas, and (2) low environmental costs. The potential for generating hydropower without dams has promise in rural areas of the US [60], Europe [16], Africa [61], and Asia [58,62]. Irrigation systems [62] and waste-water streams provide opportunities for damless hydropower generation. With respect to our question, whether it is more sustainable to build more-small vs. fewer-large hydropower projects, solutions that avoid dams can clearly be distributed in tributaries, leading to high social and environmental sustainability, but lower economic value than similar projects at dams. This would be particularly advantageous in locations where human populations are sparse [63], access to an electricity grid is lacking, water storage is not an important need (i.e., that could be provided by impoundment), or when environmental costs of damming are unacceptably high.

2. Spatial decisions

In this synthesis, we present a portfolio-based vision of sustainable river development for hydropower that focuses on spatial decisions. As noted by Hof and Bevers [13], most practical problems in resource management are matters of spatial optimization. The challenge of sustainable hydropower is no exception, and spatial optimization is critically important for maximizing energy and ecological benefits to society, both in developed river basins and those undergoing development.

We focus here on spatial decisions about where to site or remove dams. Spatial decisions in rivers have been guided by two approaches that are opposite sides of the same coin. One approach seeks to design freshwater conservation reserves where hydropower development is excluded. The other approach seeks to select dam locations based on energy and environmental considerations (Table 1). These approaches differ in the way they formulate problems and the dimensionality of habitat (1 vs. 2-dimensional), but share methods used to find solutions. Both approaches have used formal spatial optimization methods or less-formal score-and-rank prioritization methods (Table 1; Supplement A). Most studies addressing these questions in a formal quantitative manner come from the ecological literature, rather than the engineering literature. We summarize the characteristics of studies that have been used to make spatial decisions in river basins, with an emphasis on those that we deem to be more relevant to hydropower (Table 2). Decision tools can clarify trade-offs and complementarities between energy and ecological objectives and help to guide sustainable hydropower development in rivers.

Society will derive more value from provisioning services, such as hydropower, and from healthy aquatic ecosystems by paying attention to where dams are sited and by selectively reconnecting fragmented reaches. Siting decisions can be broken into choices about which tributary basins should be developed for hydropower (or not developed) and the spacing of dams within developed subbasins. It is assumed by most literature that we reviewed that dams are impassable by aquatic biota. Below, we organize our review by addressing four practical questions: (i) Is it better to build fewer mainstem or more tributary dams? (ii) Is it better to cluster dams within subbasins or to distribute them among subbasins? (iii) How should dams be spaced along individual rivers? and (iv) At what scale should spatial decisions be made?

2.1. Is it better to build fewer mainstem dams or more tributary dams?

Trade-offs between hydropower and ecological value can be described using a Pareto-optimal frontier, as defined in Table 3. At the two extremes along the frontier, illustrated by Fig. 1, a configuration without dams would provide the highest ecological value, and the configuration of many dams would provide the highest energy value. Between these two endpoints lie other configurations that balance ecological and energy value. Solutions falling below the curve should be avoided because better options exist with respect to at least one of the objectives (solid line, Fig. 1).

Hydropower value—Potential energy value is proportional to the product of hydraulic head (estimated by stream slope) and