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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

**Table 1**
Management of river portfolios has been guided by freshwater reserve design and network models, each of which has advantages and limitations. Either can use spatial optimization and either can be used for prioritization.

| Approach | Advantages | Limitations |
|---|---|---|
| Freshwater reserve design | An existing tool (Zonation, https://github.com/cbig/zonation-tutorial) is available that enjoys broad support from a user community. Other tools (MARXAN, http://www.uq.edu.au/marxan/) use formal spatial optimization to seek globally-optimal configurations. | Zonation design reserves by prioritizing removal or addition of planning units. Prioritization does not necessarily lead to globally optimal solutions. |
| | Well-suited for maximizing biodiversity contained in reserve, where current-day (static) species distributions are of primary interest. | Cannot represent dynamic objectives; instead static user-provided landscapes characterize each objective (e.g., biodiversity, cost) |
| | Design considers economic costs associated with spatial planning units, such as land-purchase cost. | Design does not consider costs relevant to hydropower, such as capital costs associated with passage structures or operational costs associated with changes in flow release schedules. |
| | Flexible user-provided relationships can be incorporated to tailor the design. | Tailoring design involves using arbitrary penalties to achieve desired outcomes, such as spreading-out reserves or forcing upstream watersheds into a solution. |
| Spatial optimization to identify optimal locations for dams | Flexible enough to address energy and ecological objectives that must be quantified using stochastic and/or dynamic models. | Development and implementation of stochastic and/or dynamic models requires more effort and resources than static maps and deterministic models. |
| | Decisions about where to reconnect river segments or site dams are integer programming problems. Complete enumeration may be a feasible solution method. | If complete enumeration is not feasible, familiarity with tools of operations research is needed to efficiently solve for globally optimal solutions. |
| | Network models can be used to describe river topology and can be used in combination with spatial optimization. | Spatial and temporal variation in river habitat quality are not easily represented using network models [14] |

**Table 2**
Studies of spatial decision support for river basins, with complete representation of those focused on hydropower and partial representation of those more-generally focused on design of freshwater reserves.

| | | **Paulsen and Wernsted [15]** | **Kuby et al. [16]** | **Schick and Lindley [17]** | **Null et al. [18]** | **McKay et al. [19]** | **Kocovsky [20]** | **Jager et al. [21]** | **Zheng et al. [22]** | **O'Hanley [23]** | **O'Hanley et al. [24]** | **Ziv et al. [25]** | **Hermoso et al. [26]** | **Theime et al. [27]** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of spatial decision | Decision about dam siting | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ |
| | Decision about dam removal | ○ | ● | ● | ● | ● | ● | ○ | ● | ● | ● | ○ | ○ | ○ |
| | Decision about passage | ● | ● | ● | ○ | ● | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ |
| Methodology | Reserve design | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ● |
| | Network model | ○ | ○ | ● | ○ | ● | ○ | ○ | ○ | ● | ● | ○ | ○ | ○ |
| | Spatial optimization | ● | ● | ○ | ● | ○ | ○ | ○ | ● | ● | ● | ● | ○ | ○ |
| | Prioritization (rank & score) | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ● | ○ | ● |
| Problem formulation (scope) | Energy | ● | ● | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ |
| | Economics | ● | ● | ○ | ● | ○ | ○ | ○ | ● | ● | ● | ○ | ○ | ○ |
| | Connectivity | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Type of ecological objective | Habitat | ○ | ● | ● | ● | ● | ● | ○ | ● | ● | ● | ○ | ○ | ○ |
| | Diadromous species | ● | ● | ● | ● | ○ | ● | ○ | ● | ○ | ○ | ● | ○ | ○ |
| | Diversity or multiple species | ● | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ● | ● | ● |
| | Invasive species | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ |
| | Dynamic objective | ● | ○ | ○ | ○ | ○ | ○ | ● | ● | ○ | ○ | ● | ○ | ○ |

river flow. Flow increases downstream as tributaries contribute flow from larger catchment areas, but slopes can be steeper in headwater catchments. The distribution of feasible new power development reflects these spatial considerations [28-30]. On a per-unit-energy basis, building fewer large mainstem dams is generally more cost-effective than building more dams on smaller rivers because of the high capital cost of building dams and associated infrastructure. Furthermore, the addition of turbines to generate electricity adds secondary value to water supply, a primary function of mainstem dams with large storage volumes.

Hydropower projects downstream on mainstem rivers tend to generate more electricity, as illustrated for US projects (Fig. 2).

**Table 3**
Definitions of terms used in spatial decision support, designing freshwater reserves, and modeling metapopulations.

| Term | Definition |
|---|---|
| Decision variable | Spatial alternatives or "configurations", i.e., for locating or removing hydropower dams, for providing passage, or for designating freshwater reserves |
| Objective | Measure of ecological and energy value to be maximized or cost to be minimized. |
| Constraint | Requirement that bounds the solution of the optimization problem. For example, instead of using hydropower production as an objective, one could seek solutions that maintain a constant level of hydropower production. |
| Global solution | A single unique, solution (spatial configuration) that maximizes the specified objective(s). |
| Pareto-optimal frontier | Graphical boundary between non-dominated solutions (i.e., no solutions exist that are better with regard to all objectives) and solutions that reduce the efficiency of one or more objectives. This frontier reveals trade-offs among objectives. |
| Prioritization model | Either a network model used to rank individual dams by their influence on access to upstream habitat or a reserve-design model used to rank spatial planning units by their individual influence on the ecological objective. See Supplement A for details. |
| Spatial planning unit | Smallest contiguous area used in forming reserves (see 'decision variable') |
| Metapopulation | A collection of populations connected by spatial colonization and extinction dynamics. We use the term to refer to any such collection of spatially structured populations. |
| Source vs. sink | 'Source' habitats support growing populations and export excess production even when receiving no immigrants. Populations in 'sink' habitats decline when isolated. |

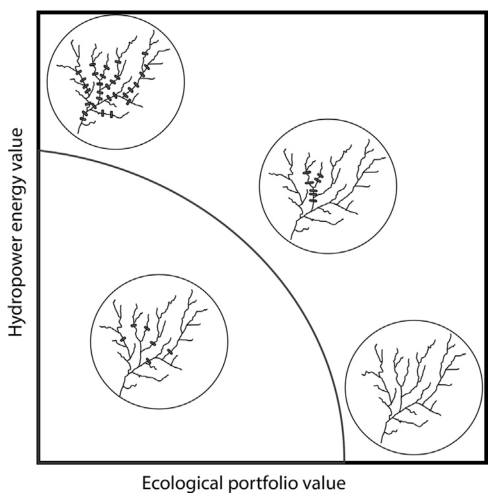


**Fig. 1.** Conceptual diagram of a Pareto-optimal frontier (solid curve) illustrates the idea that there are trade-offs between energy value and the value of ecological portfolios involved in choosing a configuration of dams in a river network. Bars on the river network diagrams denote impassable dams. We illustrated three hypothetical network configurations on the frontier, including the extremes of high energy value (circle, top left), high ecological value (circle, bottom right), and a configuration leading to moderate value for both dimensions (center circle above frontier). The river network in the circle below and to the left of the frontier is sub-optimal with respect to at least one of the two objectives, suggesting that better solutions (i.e., those along the frontier) are possible.

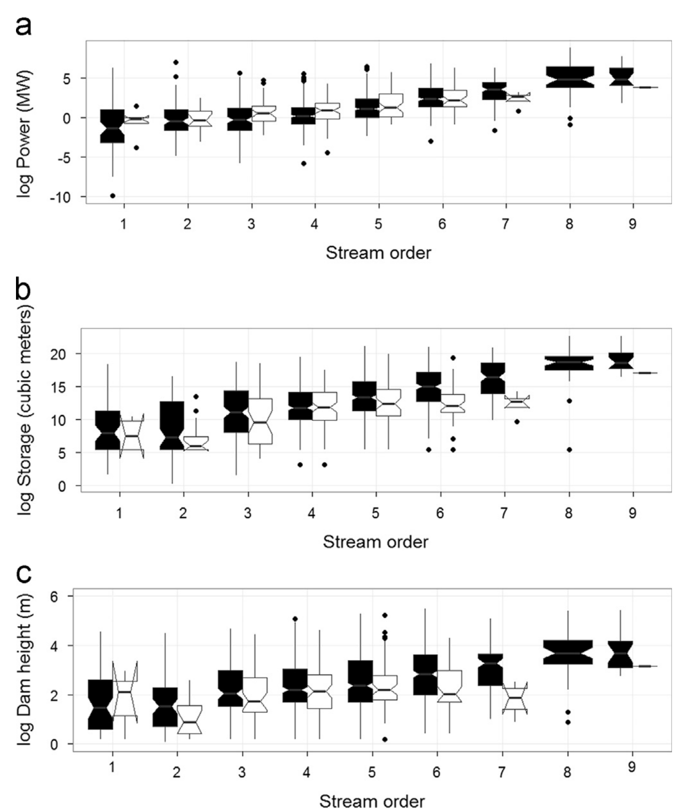


**Fig. 2.** US hydropower projects show increasing patterns in (A) hydropower generation capacity (MW), (B) reservoir storage ($m^2$), and (B) dam height (m) with downstream stream order. These increasing trends are steeper for hydropower projects with integral power houses (filled) than for those with diversions (open). Data from the USDOE Office of Energy Efficiency and Renewable Energy's National Hydropower Asset Assessment Program at Oak Ridge National Laboratory, HydroGIS, which can be accessed here: http://nhaap.ornl.gov.

Energy potential is reliably high in rivers draining large areas because flows are higher and more consistent than those in smaller tributaries. In addition to benefits associated with hydropower, mainstem reservoirs play an important role in water storage and supply. Mainstem reservoirs tend to store more water than those in tributaries (Fig. 2b). Downstream projects with integral power plants (i.e., without diversions) also tend to be associated with taller dams (Fig. 2c).

*Ecological value*—Which causes more habitat loss per unit hydropower, large or small dams? Environmentalists have argued that mainstem dams can have larger impacts, particularly on connectivity and fish passage, than a larger number of smaller dams within tributaries [31]. Large dams may inundate less area on a per-unit-energy basis than small ones [32]. In addition, smaller dams with bypass reaches can experience substantial habitat degradation during periods of low flow if no minimum flows are required [33]. These two alternatives are illustrated by Fig. 3, with Fig. 3a and c representing configurations with more tributary dams and Fig. 3b and d representing configurations with the majority of capacity in a smaller number of dams located on the mainstem.

How dam placement influences access to habitat in rivers depends on the interaction between spatial life histories of the species and the topological properties of the river networks they inhabit. In two-dimensional habitats, animals have the option of going around barriers. In rivers, placement of the first dam in a river network has a larger impact than subsequent dams because options for access by fish to other reaches are restricted [34,35]. Different configurations of dams may be favored depending on whether the aquatic community includes species that make short,

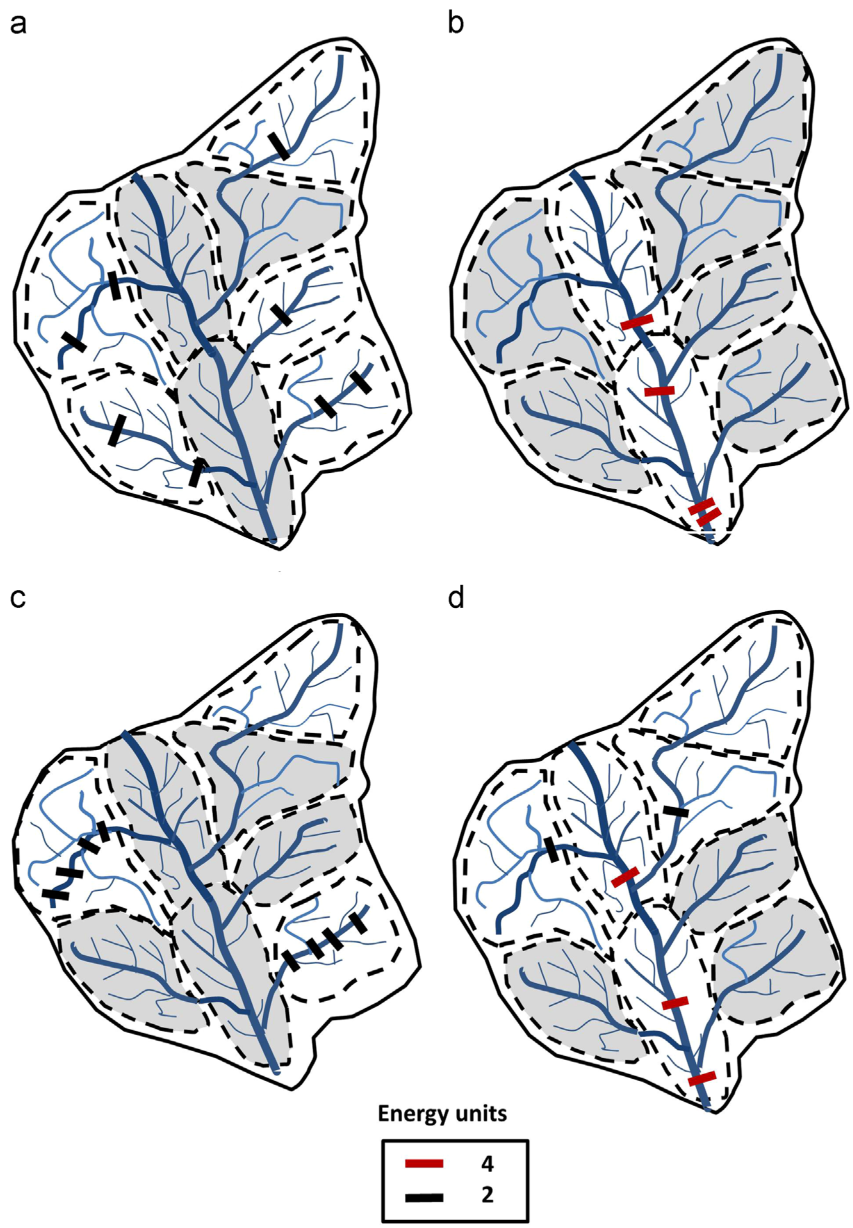


**Fig. 3.** Alternative configurations of dams summing to 16 energy units by a combination of impassable dams with different hypothetical generating capacities: (a) small dams distributed among tributaries (connected core reserve); (b) large dams concentrated in the mainstem block the basin outlet (tributary reserves avoid spatially correlated risks); (c) small dams clustered within a few tributaries (large connected core reserve); and (d) a combination of large and small dams spaced far apart often with tributary habitat between dams (few tributary reserves). Shading indicates freshwater reserves, defined here as catchments without dams.

local migrations, species that make long migrations within river (potadromous), or diadromous fishes. Even in river basins without ocean access, it might make sense to protect downstream basins and build dams in tributaries because fish biodiversity generally shows a nested pattern of increase as tributaries join the river [36]. Two counter-arguments are that headwaters make up the majority of river habitat and that protection of upstream tributaries can also benefit downstream reaches. Headwaters of some river basins (e.g., mountainous regions) may support distinct, locally endemic species that evolved in isolation, for example darters in the southern Appalachian mountains. Downstream benefits of upstream protection might be expected when tributary development will significantly degrade water quality [37] or when tributary fish populations are critical demographic sources supporting downstream populations.

Most studies seeking to identify where it is best to site or retain dams have focused on migratory fishes because these species are among those most affected by dams. All but six coastal US rivers block migrations longer than 200 km between river basins and their estuaries [3], and this loss of access to coastal rivers has contributed to the imperilment of diadromous fishes [38].

Diadromous species are most impacted by large dams at the outlets of downstream river basins. Studies of dam removal options in coastal US river basins all reached this conclusion. In the Willamette Basin, USA, removing downstream dams provided migrating salmon with the greatest access to upstream drainage area [16]. Economic losses were minimized by choosing downstream dams impounding reservoirs with smaller storage capacity. For tributaries of Lake Erie, optimal solutions removed dams near river mouths blocking long stretches of upstream walleye habitat and with little risk of introducing lamprey [22]. As in the Willamette Basin study, smaller dams were removed in optimal solutions when economic considerations were added. Null et al. [18] evaluated trade-offs between water storage, hydropower, and access to habitat for anadromous salmonids in California under baseline and future climate conditions. A subset of "rim" dams (large multi-purpose dams at low elevations of tributaries to the Sacramento and San Joaquin Rivers) were targeted because their removal added access to considerable habitat for salmon with minimal reductions in total hydropower. Because water supply was an important provisioning service, dams were treated as part of an inter-connected system rather than as independent entities. Thus, the ability to remove some dams depended on keeping and maintaining others (e.g., Shasta and Oroville Dams) [18].

Studies using graph (network) theory also suggest that dams located near downstream river basin outlets reduced network connectivity more than dams located in tributaries. Studies in the Truckee River, NV [19] and the Sacramento-San Joaquin Rivers, CA [17,18], identified dams near basin outlets as those with the largest impacts on access to spawning habitat by salmon. A similar solution was reached through a cooperative agreement among stakeholders in the Penobscot River basin, Maine, whereby selective dam removal is not expected to result in energy loss, but shad and Atlantic salmon are projected to gain increased spawning habitat (Box 1).

Optimization studies in river basins of developing countries typically focused on the question of where to add new dams, rather than where to remove dams or add upstream passage. In general, within river basins supporting migratory fishes, solutions that sited dams in tributaries had the lowest simulated ecological impact. Barradas et al. [39] concluded that a proposed new tributary dam would cause less ecological harm to four migratory fishes found in large, low-altitude rivers in Uruguay than alternative sites farther downstream. Ziv et al. [25] maximized the number of migratory fishes protected subject to energy production targets by simulating increasing subsets of proposed new dams in the Mekong River basin. Locating all dams on the lower mainstem had the largest adverse impact on migratory fish biodiversity. Locating one dam upstream on the mainstem and adding limited tributary dams had the lowest impact. In a scenario without mainstem dams, in-river migrants benefitted most when tributary dams were built upstream first, leaving downstream reaches of main tributaries and the Mekong River accessible. As energy demand increased, downstream dams were added to optimal configurations of tributary dams [25].

Together, these studies suggest a trade-off between energy and ecological values. Dams in tributaries are less harmful to migratory fishes, but larger, mainstem dams with larger contributing flow and storage may have higher energy value. In river basins with steep tributaries, both objectives may be satisfied by tributary dams. In some cases, both objectives can be satisfied by avoiding placement of mainstem dams with low value for hydropower production. However, mainstem reservoirs also supply other non-hydropower services, such as water storage and supply and provide more opportunity for releasing water during times of peak demand when electricity prices are high.

### 2.2. *Should dams be clustered or distributed among distant sub-basins?*

To maximize ecological value, we hypothesize that risk to the river portfolio can be reduced by (i) clustering dams within fewer tributary basins (i.e., Fig. 1c, not Fig. 1a) and (ii) including connected freshwater reserves that serve as migration corridors (Fig. 1a and c).

Thus far, studies seeking to optimize connectivity have favored protection of a single, accessible network, rather than multiple, dispersed corridors. In a study of the Pike River, Wisconsin, USA, the optimal configuration included one cluster of connected reaches [23,24]. In this example, dams were selected to maximize total accessible quality-weighted habitat for fishes migrating within freshwater (i.e., not species requiring access to the ocean). Removing dams nearest to a maximally-connected sub-network opened up adjacent watersheds for colonization by fishes.

Reserve design addressed the same problem from the opposite direction, asking the question, *Which catchments should we protect?* instead of *Where should we place or remove dams*? When freshwater reserves were ranked by connectivity, reserves following catchment boundaries had higher priority [40]. Thus, reserve design produced the same result as formal optimization in this case, producing one large, connected network.

Despite the fact that studies using different approaches converged to give one answer, we still consider the question of whether to cluster dams or disperse them among subbasins to be unresolved. Neither approach has thus far addressed spatial interactions in how decisions in one place affect objectives in another. Two important classes of spatial dependencies discussed below are upstream–downstream relationships and dependencies among branches in a dendritic network.

*Dependencies between upstream and downstream reaches*—In rivers, strategic decisions regarding upstream and downstream planning units (e.g., reaches) can hardly be made independently. Therefore, decision making methods that use a sequential prioritization are not likely to produce optimal results [41]. In reserve design, it may be important to protect ecosystem services in a river from upstream watershed development. When considering which dams to remove, it makes little sense to remove an upstream dam for diadromous fishes unless the dam can be reached from the ocean without encountering other barriers. Thus, the decision to add or remove a dam upstream is not independent of the decision to add one downstream. Another example is the benefit of adding a dam downstream of upstream projects to stabilize the hydrograph farther downstream and thereby improve fish habitat. Removing the re-regulating dam would have a cost (degrading tailwater habitat) not accounted for by current methods.

To date, upstream–downstream dependencies have been addressed either by adding a constraint (i.e., an upstream dam will not be removed unless those downstream are as well), or, by adding a penalty for not including upstream planning units. By increasing this penalty, produced freshwater reserves produced by Clavero and Hermoso [42] ranged from (i) a diffuse collection of isolated reserves to (ii) a reserve made up of a linear corridor of units to (iii) units clustered within catchments. The penalty strongly influenced the final configuration of reserves, yet it is unclear how large the penalty should be.

*Dependencies among branches*—Most studies above produced optimal configurations that aggregated reserves. This may be because studies did not consider processes that would reduce extinction risk for disaggregated reserves, such as spatially autocorrelated exposure to risks. Aggregating protected reaches in one catchment elevates exposure to spatially correlated risk. On the other hand, if disturbances follow watershed boundaries, then a dendritic (i.e., branching) spatial arrangement of populations should promote persistence of the larger metapopulation by spreading risk [43]. However, colonization is more likely when a population in one reach has a population to support it nearby. How topology influences colonization and extinction dynamics in dendritic ecological networks is an interesting and growing area of research [44-46].

Many riverine populations exist as a loosely coupled network of spatially structured populations (here we use the term 'metapopulations' as defined in Table 3). Metapopulations enjoy a lower overall risk of extinction because stream reaches where populations are extirpated can be recolonized by neighboring populations Salmon populations from distant watersheds fluctuate independently whereas fluctuations in neighboring populations are synchronized [47]. In the Columbia River basin, Chinook salmon that breed in different tributaries are correlated within (but not among) large basins [48]. From the standpoint of ecosystem services, asynchronous populations are substitutable resources; they serve similar functions and are collectively less susceptible to disturbances.

Among studies reviewed here, few addressed the potential added ecological value of distributing reserves among tributary basins. Using a metapopulation model, the added risk of extirpation caused by clustering reserves can be included by simulating colonization–extinction dynamics for species in river habitats exposed to disturbances [49]. It seems reasonable to expect some spatial autocorrelation, but beyond this, it is difficult to anticipate what the spatial properties of future disturbances might be. In one example, Moilanen et al. [50] imposed a distance penalty to reduce the value of the objective function for proposed reserves that included closely-spaced reaches. However, it is unclear how an appropriate penalty should be estimated, except through modeling spatial processes.

The ecological benefits of a well-designed freshwater reserve extend beyond its borders because protecting source habitat should increase recolonization rates in non-protected habitats. For example, source habitat can be protected through judicious placement of protected tributaries or restoration of floodplains used for breeding or rearing. Restoring sink habitat to become sources can also be a good strategy [51]. Improving water quality in a reservoir where poor conditions have prevented successful fish reproduction is one example of this approach.

Whether or not to cluster dams within fewer tributary basins seems to be an energy-neutral decision. However, there may be energy-related considerations. Clustering dams allows infrastructure to be shared (e.g., water from several dams can be diverted to shared downstream generating units). On the other hand, the risk of power shortages related to drought (insufficient reservoir inflows) can be buffered by spreading dams across sub-basins with different weather and flow patterns.

To conclude, we advance the hypothesis that concentrating dams within a subset of tributary basins will lead to higher ecological value for a given level of energy production than distributing dams across all tributary basins with a lower density of dams in each basin. Secondly, we propose that it is better to distribute freshwater reserves among the remaining tributary basins to spread risk across the ecological portfolio and preserve upper portions of migration corridors. However, studies are needed to support or refute these proposals.

### 2.3. *Where should dams be placed along a river?*

Once it has been decided that a sub-basin is to be developed, the next question is where dams should be placed along a single river. To date, few studies have addressed optimal dam spacing or cumulative effects of dams on energy and ecological objectives.

*Hydropower value*—From the standpoint of hydropower production, placing dams in series is desirable because the same parcel of water can be used to generate electricity at each dam. Close spacing between dams diminishes energy generation only when one dam backs water up so that the water surface elevation below the dam is above the foundation of the next dam upstream and hydraulic head, the gravitational energy of water, is reduced. Recent studies using GIS have identified sites with high potential for new hydropower generation in the USA [28,29] and Europe [30].

*Ecological value*—Few field studies have focused on understanding how the interspersion of unregulated sections of river with reservoir and tail-water habitats affects riverine communities. Sequential dams affect downstream water quality and alter access to habitat areas [9], but there is no consensus on whether downstream ecological impacts of sequential dams are greater than those of individual dams. Changes (e.g., loss of floodplain habitat, reduced nutrient and sediment transport, altered temperatures) can be compounded by adding more dams on the same river. However, the downstream effects of low-head dams are not necessarily cumulative [52]. One reason is that upstream flow alterations can be mitigated by downstream dams that store water released from upstream facilities during peak demand. This re-regulation protects the downstream river ecosystem from large diurnal fluctuations in flow.

Whether a reach between two dams can sustain a population of a given species is, in part, a function of the length of undammed river between the dams. Dams may interrupt the “conveyer belt” spatial life history pattern of some species in which adults move upstream to reproduce in lower-order reaches with fewer predators, and juveniles move downstream as they grow less vulnerable to gape-limited predators and become able to consume larger prey. Many riverine species have early life stages that drift downstream. By spacing dams far enough apart, juveniles are more likely to be retained in the intervening reaches. Otherwise, juveniles drift past the downstream dam with no way to return upstream to complete their life cycles.

Tributaries and floodplains are particularly valuable as spawning and nursery areas. Tributary confluences serve as hot spots for spawning for some fishes because they provide heterogeneous substrates and flows [53]. Unregulated tributaries between dams can extend the free-flowing habitat between dams [54]. Sinuous, slow, and vegetated floodplain habitat along river margins also slows drifting juveniles, encourages settling, and offers them protection from predators.

Few modeling studies have addressed the question of how to space dams. One study divided a fixed length of river into the same number of short and long river segments, where the long segments were demographic ‘sources’ and short segments were ‘sinks’ (Table 3), and where short segments tended to have little to no free-flowing river (all reservoir). Simulated population sizes were largest when the source segments were upstream and source and sink segments were interspersed [34]. McKay et al. [19] identified a threshold number of dams beyond which connectivity was dramatically reduced, regardless of watershed topology and dam configuration.

We hypothesize that spacing dams farther apart than needed to maximize hydropower can promote ecosystem services, particularly upstream (Fig. 3d). However, closer spacing may be possible for reaches having adequate nursery habitat (e.g., floodplain, tributaries) in between. All design principles may not be met simultaneously. For example, providing mainstem corridors (Fig. 3c) precludes spacing dams far apart in the remaining tributary catchments, and vice-versa (Fig. 3d). To date, few ecological models used to address spatial decisions about dam placement have included features (e.g., larval drift, upstream water quality, turbine mortality) needed to find realistic optimal configurations.

### 2.4. *At what scale should spatial decisions be posed?*

Spatial scale is characterized by extent and resolution. The boundaries (extent) used to frame decision problems can be important because they influence which aspects of sustainability (e.g., economic, ecological, social) are favored. Whereas decisions are often made using political boundaries, collaboration among government entities and other stakeholders may be sufficiently flexible to use watershed boundaries that are relevant to aquatic biota [55].

**Box 2–**The case of the Penobscot River basin.

On Maine's Penobscot River, a hydropower company, the Penobscot Indian Nation, various governmental agencies, and conservation groups negotiated an agreement to remove two dams (Fig. 4) and bypass a third, while increasing energy generation at the remaining dams. As a result, the extent of river habitat available to migratory fishes—including Atlantic salmon, American shad, alewife, American eel, striped bass, shortnose and Atlantic sturgeon—will increase dramatically. For example, Atlantic salmon will gain access to approximately 1000 additional miles of spawning habitat. Fisheries biologists forecast the basin's salmon population will increase three to four fold. Capacity and operational changes at remaining dams are projected to maintain or slightly increase hydropower generation [51]. This agreement illustrates that basin-scale approaches can provide a broader set of solutions for balancing energy and riverine environmental resources than can be achieved by individual projects.

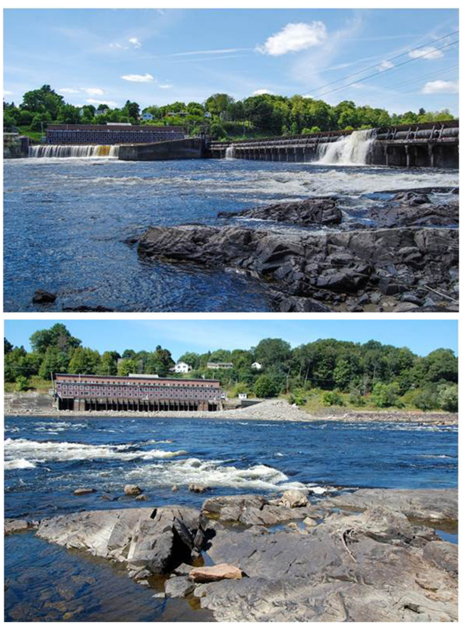

**Fig. 4.** Veazie Dam, one of two downstream dams on the Penobscot River in Maine, USA, was removed in 2013 as part of a basin-wide settlement agreement among stakeholders. Before (top) and after (bottom) photographs taken by Josh Royte of the Nature Conservancy (used with permission).

We advance the hypothesis that making spatial decisions about hydropower development at the extent of large river basins and the resolution of smaller watersheds as planning units will produce solutions with higher ecological value that accommodate sustainable hydropower development. The management of large rivers requires the alignment of decisions with the scale of metapopulations, which span multiple rivers [56]. Furthermore, expanding the geographic scope of a decision allows for a broader range of potential solutions and higher overall benefits [57]. For example, a settlement agreement in the Penobscot River basin in Maine, USA focused at the scale of the basin resulted in a more balanced outcome between energy and fisheries (Box 2).

## 3. Summary

We have outlined a vision for spatial decision-making to guide environmentally sustainable hydropower development. Our review focused on where to locate dams and where to reconnect river segments above and below dams to balance objectives for hydropower generation and ecological viability. However, we recognize that other types of ecosystem services also contribute to river portfolios. We identified areas where we see opportunities for advancement, including (i) consideration of spatial colonization–extinction dynamics, (ii) better integration of hydropower as an objective and cost, and (iii) improved consideration of dam-associated influences on habitat and survival (e.g., water quality, entrainment risk). In addition, more exploration of the potential for damless hydro [58] and how these might fit into a well-designed river portfolio is needed.

Synthesizing past efforts led us to propose 'riverscape' design principles to guide ecologically sustainable development of river basins for hydropower: (i) within a large river basin, concentrate dams within a subset of tributary watersheds and avoid placing hydropower facilities on a downstream mainstem, (ii) disperse freshwater reserves among remaining tributary watersheds, (iii) ensure that habitat between dams will support and retain biological production, and (iv) formulate spatial decision problems at the scale of large river basins. Further research is needed to test these proposals, and we hope that future refinements of these hypotheses will suggest new insights in this growing area of applied science.

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## Appendix A. Supplementary materials

Supplementary materials associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2015.01.067.

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