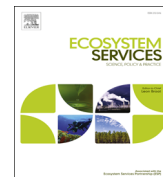




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Beyond the concrete: Accounting for ecosystem services from free-flowing rivers



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ABSTRACT

People derive benefits from river networks under free-flowing conditions, through ecosystem services such as fishery yield, floodplain agriculture, desirable geomorphic form, and the cultural significance of native riverine biodiversity. However, water management decisions have historically emphasized the production of ecosystem services such as hydropower and irrigation that depend on the construction of extensive infrastructure. Such decisions typically impose tradeoffs that reduce benefits from free-flowing services, yet neither these losses nor the costs of future ecosystem rehabilitation have been well represented in decision support analyses. Ecosystem service assessments can and should account for benefits in the absence of water infrastructure to inform balanced water policy and watershed management.

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1. Beyond infrastructure-dependent services

Freshwater availability is a fundamental driver of local economies and ecosystem states, and societies have depended on rivers for millennia (Wohl, 2010; Fagan, 2011). Governments, corporations, and communities can and should account for a diverse portfolio of river-derived ecosystem services as they decide how best to manage surface water resources in the challenging context of global climate change and population growth (Engel and Schaefer, 2013; Ormerod, 2014). Such accounts may reveal choices that sustain desired ecosystem functions while delivering equitable economic gains (Fisher et al., 2008; Ruckelshaus et al., 2014). Yet, ecosystem service assessments must account for more than water uses that rely on dams, levees, and diversion channels if they are to adequately characterize tradeoffs in watershed management.

Industrial-scale interventions and infrastructure within river corridors have played a fundamental role in historic trends of economic development, and “hydrologic ecosystem services” such as hydropower and out-of-channel water supply to irrigators, municipalities, and private firms have received considerable attention within the burgeoning field of research on ecosystem services (Brauman et al., 2007). For example, programs of payment for watershed services often involve infrastructure owners compensating upstream stakeholders to modify their agricultural and forestry practices in ways that are intended to secure profitable operations and intact terrestrial habitats (e.g., by reducing reservoir sedimentation or dampening discharge fluctuations; Guo et al. (2000, 2007); Martin-Ortega et al. (2013); Wunder (2013); Fu et al. (2014)). However, extensive water infrastructure involved in delivering these hydrologic services has deeply altered the character of many river networks, with largely detrimental consequences for native species composition, nutrient cycling, and the form of banks, floodplains and deltas (World Commission on Dams (WCD), 2000; Brismar 2002; Bunn and Arthington 2002; Nilsson et al., 2005; Naiman and Dudgeon, 2010). These changes have weakened or excluded the production of naturally generated services, sometimes irreversibly.

The ecosystem service paradigm provides a cogent conceptual background within which to represent these tradeoffs and extend applied decision support analyses beyond the traditional

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Table 1
Likely effects of water infrastructure such as dams, levees, canals on ecosystem service values. In both developed and developing economies, many current policy and management decisions are based on well-recognized benefits derived from off-channel use of diverted surface water and in-channel use of water for industrial activities. Yet decisions to maximize benefits from these services tend to impose tradeoffs against services that are generated in the absence of significantly altered regimes of flow, sediment, temperature and nutrients. Quantified production and benefit functions as well as safe minimum standards for these “free-flowing” ecosystem services remain a research need, especially relative to the established methods and knowledge concerning services that depend on extensive infrastructure. See [Wilson and Carpenter \(1999\)](#), [National Research Council \(NRC\) \(2004\)](#), [Brauman et al. \(2007\)](#), and [Korsgaard and Schou \(2010\)](#) for further examples and citations.

Ecosystem service	Δ	Primary beneficiaries	Notes and examples
Diverted water for agricultural, municipal, industrial, and extractive energy use	+	Individuals, firms	Diversion may involve major in-channel structures and reservoir storage, off-channel conveyance and storage, or “as available” use requiring minimal construction within the river corridor.
Hydropower generation and thermoelectric cooling	+	Firms, states	Historically, these services have been fundamental to industrial economic development worldwide.
Transportation of people and materials	+/-	Individuals, firms, states	Industrialization has increased shipped volumes via dredging and channel reconfiguration, but realization of these services pre-dates heavy infrastructure interventions. Traditional use and access to rivers for transport may depend on flow and sediment regimes that dams alter.
Recreation and esthetic appreciation	-/+	Individuals	Reservoirs and flow regulation by dams may create new opportunities for boating and non-native sport fishing. They may simultaneously diminish benefits from non-motorized boating, native sport fishing, and wildlife viewing in the river corridor. Similarly mixed effects may occur for residential and commercial property values near channels and former channels. Likewise, major infrastructure projects may be regarded as a source of cultural pride or devastation.
Food and fiber from the river corridor	-/+	Individuals	Dams and levees tend to disfavor traditional and commercial in-channel harvests by disrupting reproductive cues and migrations, by disconnecting spawning habitats, and by facilitating populations of harmful non-native aquatic species. Similarly, major infrastructure may impair historically sustainable floodplain agriculture by ending periodic flushing and renewal of soil fertility.
Insurance from water-related catastrophes	-/+	Individuals, firms, states	Reservoirs may be operated with flood control objectives, but may also result in inadvertent bank stabilization and channel incision that increase flow velocity and hinder natural energy dissipation during high flows, thereby increasing the severity of large floods. Trapping of sediment in reservoirs, particularly in river systems with multiple dam sequences, may also lead to erosion of delta landforms, potentially rendering coastal population centers vulnerable to greater storm damage.
Preservation of native biodiversity	-/+	Individuals	Infrastructure that substantially contributes to species extinctions imposes an irreversible loss of natural heritage (a cost in terms of existence value) and sacrifices future enjoyment for the sake of present desires (a cost in terms of bequest value). However, in heavily managed river systems, unanticipated opportunities may arise to operate infrastructure in ways that favor threatened biota (e.g., intentional flooding to stimulate reproduction). In general, the intergenerational legacy of infrastructure is a complex mix of ongoing capital and maintenance costs, restoration costs following decommissioning, and opportunity costs under changing social and environmental conditions.
Pollutant removal and disease transmission risk	?	Individuals, states	Infrastructure that slows water velocity and impairs riparian ecosystem function creates the potential for concentrated contaminant “hotspots” of inorganic pollutants that require expensive, difficult remediation. In addition, dams and levees may harm species such as freshwater mussels that naturally regulate water quality. Reservoirs may raise the risk of undesirable eutrophication, but additional research is warranted regarding the consequences of infrastructure for the processing of nitrogen, phosphorous and other organic compounds as well as for the conveyance of water-borne pathogens or the abundance of disease hosts.

emphases of water resource management. Ecosystem service assessments may effectively capture the opportunity cost of benefits lost with infrastructure construction and may highlight the benefits of river restoration and future decommissioning costs. Nonetheless, routinely conducting such assessments will require researchers and practitioners to overcome two basic and related challenges: the set of ecosystem services produced under free-flowing conditions must first be recognized, and these “free-flowing services” must then be consistently integrated into assessments.

2. Recognizing the benefits of free-flowing rivers

Ecosystem service assessments have an important role to play in raising awareness of the benefits of free-flowing rivers among decision makers, particularly in wealthy nations where dams, diversions, levees, locks, and related water infrastructure are now so prevalent as to be largely societally ingrained. We describe several examples in this section, and [Table 1](#) compiles changes likely to follow construction of extensive hard infrastructure, drawing from comprehensive treatments of ecosystem services directly related to

surface water quantity, quality and timing ([Wilson and Carpenter 1999](#); [NRC, 2004](#); [Brauman et al., 2007](#); [Korsgaard and Schou, 2010](#)).

Fisheries and recreational enjoyment of rivers are prominent among the benefits that may decline with the intensification of hard infrastructure. Though novel recreation may arise on reservoirs or in their tailwaters (e.g., angling for introduced fish species), recreational activities such as rafting or wildlife viewing can suffer with dam construction, and numerous studies have described the detrimental effect of dams on fish-related services ([Holmlund and Hammer, 1999](#)). Important commercial and subsistence stocks of both freshwater and diadromous species, such as salmon, may suffer as a result of habitat fragmentation and loss, introduction of competitors and predators, and the elimination of spawning cues. For example, [Hoeinghaus et al. \(2009\)](#) found that populations of native, high-value species declined after impoundment of the Paraná River (Brazil), and that annual total yield decreased from more than 1500 to less than 1000 t despite an increase of effort from less than 70,000 to more than 120,000 fishing days. Conversely, [Butler et al. \(2009\)](#) found significant local economic benefits from recreational fisheries associated with the minimally altered River Spey (Scotland), reporting that aggregate

catchment household income increased by roughly £970 for each salmon or sea-run trout caught. More generally, seasonal flood pulses on large rivers foster tremendous biological productivity, and tropical floods drive high fishery yields per unit area alongside floodplain nutrient enrichment (Bayley 1995).

Extensive hard infrastructure that affects riparian and in-channel biological communities may also reduce non-market benefits from services such as water quality regulation and floodplain maintenance. For instance, the habitat and functional diversity of freshwater mussels and other bivalves are vulnerable to river engineering and water diversion (Vaughn, 2010). Maintaining the nutrient removal and filtration of suspended matter performed by these communities could help to avoid increased water treatment needs. In contrast, the loss of such services may prompt costly remediation attempts. Strange et al. (1999) found that dam-altered flow and sediment regimes along the South Platte River (Colorado and Nebraska, USA) prompted species changes with locally undesirable effects on floodplain form and function. Aggregate household willingness to pay for riparian conservation activities via water bill surcharges ranged from \$19 million to \$70 million, indicating a strong desire to restore services lost following flow modification (Loomis et al., 2000). More broadly, the modification of flow regimes by dams throughout western North America has contributed significantly to widespread declines in native riparian species with high recreational and cultural value and has simultaneously favored undesirable non-natives (Merritt and Poff, 2010). Though unanticipated during the original benefit–cost analyses for this infrastructure, the long-term costs continue to accrue, with management responses such as removal and revegetation projects ranging from \$200 to more than \$6000 per hectare (Rood et al., 2005; Shafroth et al., 2005).

Unregulated riverine systems support unique ecological assemblages resulting from a singular evolutionary history, and these groups of species may have substantial non-use value to local and distant human communities. For instance, awareness of the services produced by a free-flowing river contributed to decisions that culminated in the removal of the Elwha and Glines Canyon dams on the Olympic Peninsula (Washington, USA). Independent of the possible benefits to commercial fisheries or other market and non-market services, Loomis (1996) found significant willingness to pay for the improved existence and bequest values (types of non-use value) associated with dam removal and the subsequent rehabilitation of native salmon populations. Extrapolating from surveys of more than 1500 households at multiple geographic scales, the annual aggregated benefit from these changes was estimated at \$138 million to residents of Washington State and \$3 billion to \$6 billion for all U.S. residents. Gowan et al. (2006) argued that pricing non-use benefits was not critical to the overall trajectory of choices concerning the Elwha, but these authors also described how ecosystem service values informed the decision-making process during benefit–cost analysis of fish passage structures (an alternative to removal) and via the cultural importance of a free-flowing river to the S'Klallam people. This example clearly indicates how quantitative accounts of the benefits that people derive from naturally variable rivers with intact habitat could inform infrastructure construction and river restoration choices in many other settings.

Finally, several studies have pointed toward increased service production and societal benefit following restoration of natural river function and structure. On the Manistee River (Michigan, USA), net gains in services followed a change in dam operations from erratic hydropeaking releases (rapidly ramped discharge levels that track daily electricity demand) to a run-of-river pattern that better resembled the natural flow regime. In this setting, unanticipated recreational and air quality benefits (due to a net decrease in coal-based thermal electricity generation) were

estimated to yield approximately \$800,000 to \$985,000 per year versus costs of \$310,000/year from lost hydropower revenue (Kotchen et al., 2006). Furthermore, in a hedonic valuation analysis controlling for a wide range of co-predictors, Lewis et al. (2008) found that real estate sales prices shifted in relation to removal of the Edwards Dam (Maine, USA). Proximity to the river corridor was undesirable prior to dam removal, likely due to perceived environmental and aesthetic degradation, and carried price penalties of \$2.43/m and \$7.30/m in two markets (i.e., home prices increased by more than \$2000 and \$7000 per kilometer away from the river). Following dam removal, this price penalty declined to \$0.16/m and \$1.80/m, respectively, as habitat and water quality subsequently improved along the Kennebec River and the benefits from services such as river recreation increased. This effect requires additional research; however, as other studies have found that dam removal and subsequent river restoration led either to no change or even to a decrease in the value of homes with direct river frontage (Provencher et al., 2008; Bohlen and Lewis, 2009).

Despite such complexities, benefit–cost ratios for new water infrastructure are likely to decrease (i.e., overall costs will increase relative to benefits) as the costs of remediation and lost free-flowing services are internalized. For instance, a retrospective approximation of the negative externalities associated with 3 of the 130 hydroelectric dams in the Jiulong River basin (China), noted that current power grid tariffs poorly reflected the high costs associated with factors such as impaired water quality and biodiversity loss (Wang et al., 2010). Amidst the growing number of major river restoration projects and the resurgent interest in large dam construction, a pressing need has arisen for research to adequately quantify the costs for decommissioning and ecosystem rehabilitation (Bernhardt and Palmer 2011; Ansar et al., 2014). Going beyond regular maintenance, such costs are likely to be substantial, particularly if they are calculated to include technical feasibility studies and legal work in addition to direct project activities such as demolition, channel reconfiguration, and mitigation of accumulated sediment (Whitelaw and MacMullan, 2002; Doyle et al., 2003).

3. Extending tools to assess free-flowing services

With the greater recognition of free-flowing services comes the need to estimate how land and water management will affect their production, particularly within the decision contexts of scenario analysis, payment for watershed services, and spatial planning (Guswa et al., 2014). This estimation will hardly be trivial: stochasticity and non-stationarity in physical processes combine with the ongoing reconfiguration of genomes and species interactions to create complex ecohydrologic dynamics. The resulting spatiotemporal diversity of ecosystem states and the potential for sharp response thresholds complicate the definition of service production functions and create tension with the desire for simplified models suited to rapid implementation in data scarce settings (Vigerstol and Aukema, 2011; Bagstad et al., 2013b; Guswa et al., 2014). Geographic disjunctions between the respective locations of service production and benefit realization (e.g., distributed controls on water quality versus a single access point) and the location-specificity of values from some non-market, non-use free-flowing services may also complicate benefit functions, reducing the relevance of generalized valuation via readily available financial data (Bagstad et al., 2013a).

Nonetheless, large bodies of research on robust valuation approaches and conceptual models of integrated watershed assessment (e.g., Letcher et al., 2007; Brouwer and Hofkes, 2008) can guide the extension of existing assessment tools to include production and benefit functions for free-flowing services

alongside those dependent on infrastructure. For example, the groundbreaking ecosystem service modeling platforms InVEST and ARIES (reviewed with 15 other tools in Bagstad et al. (2013b), and directly compared in Bagstad et al. (2013c)) will be greatly strengthened by better accounting for services such as freshwater fishery yield, river corridor recreation, floodplain fertility, and maintenance of riverbanks and deltas (supplementing current modules for the production and value of hydropower, avoided reservoir sedimentation, and freshwater supply for off-channel diversion). Adapting existing components that address marine fisheries, natural flood regulation, terrestrial biodiversity, and aesthetic quality may offer an expedient means to accomplish this model development.

Going further, a compelling direction for decision-relevant research concerns the integration of environmental flow science with ecosystem service assessment (Pahl-Wostl et al., 2013). Disruption of a river's natural flow regime and connected habitat creates the risk of irreversible, non-substitutable losses following species extinction or ecological community collapse. Consequently, holistic methods to define environmental flows have been developed to provide standards for how water allocations and watershed land use will be permitted to modify water quantity, quality, and timing (Poff et al., 2010; Arthington, 2012). The process of defining an environmental flow regime convenes multiple stakeholders to compromise on water management guidelines that retain critical natural flow attributes. From this perspective, water quantity, quality and timing have typically been viewed as controls on biological populations, but these flow regime attributes may also be analyzed as the production factors of free-flowing ecosystem services. An intuitive first step toward ecosystem service assessments informed by environmental flow science would therefore incorporate "safe minimum standards" for water quantity, quality and timing into existing modeling tools (Crowards, 1998; Fisher et al., 2008). Even in data-scarce, rapid assessment situations, simple percent-of-flow rules (Richter et al., 2011) could offer a means to specify these critical production thresholds. Ecosystem service assessment tools could then better represent how watershed management scenarios affecting hydropower generation or water diversion may influence a broader set of benefits. For example, an evaluation of a possible payment for watershed services program could effectively address whether compensating upstream landowners to protect a forest parcel could also help to sustain the low and high flow conditions required by local aquatic species.

4. Conclusion

Decision makers require a clear understanding of likely trade-offs as they contemplate choices that will alter the ecosystem function of river networks and their watersheds. Framing the consequences of management alternatives in terms of a balanced set of ecosystem services will certainly not guarantee free-flowing rivers. However, ignoring the benefits that accrue in the absence of hard infrastructure neglects much of what the life in the river brings to our lives and risks encouraging the continued impairment of freshwater ecosystems. Careful assessments of free-flowing and infrastructure-dependent ecosystem services can supplement legal environmental regulations to improve the uncertain and difficult process of water resource management.

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