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INFORMING WATERSHED CONNECTIVITY BARRIER PRIORITIZATION DECISIONS: A SYNTHESIS[†]

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ABSTRACT

Water resources and transportation infrastructure such as dams and culverts provide countless socio-economic benefits; however, this infrastructure can also disconnect the movement of organisms, sediment, and water through river ecosystems. Trade-offs associated with these competing costs and benefits occur globally, with applications in barrier addition (e.g. dam and road construction), reengineering (e.g. culvert repair), and removal (e.g. dam removal and aging infrastructure). Barrier prioritization provides a unique opportunity to: (i) restore and reconnect potentially large habitat patches quickly and effectively and (ii) avoid impacts prior to occurrence in line with the mitigation hierarchy (i.e. avoid then minimize then mitigate). This paper synthesizes 46 watershed-scale barrier planning studies and presents a procedure to guide barrier prioritization associated with connectivity for aquatic organisms. We focus on practical issues informing prioritization studies such as available data sets, methods, techniques, and tools. We conclude with a discussion of emerging trends and issues in barrier prioritization and key opportunities for enhancing the body of knowledge. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: spatial planning; aquatic landscape ecology; fish passage; aquatic organism passage; dam removal; culvert repair; dam construction

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INTRODUCTION

Freshwater ecosystems are fundamentally shaped by structural and functional connectivity (Pringle, 2001; Wiens, 2002). In particular, the longitudinal dimension of connectivity (i.e. upstream–downstream) has been significantly disrupted by barriers such as dams (Graf, 1999; Lehner *et al.,* 2011), roads (Jones *et al.,* 2000; Januchowski-Hartley *et al.,* 2013; Laurance *et al.,* 2014), and water diversions (Walters *et al.,* 2012). The scale of this modification is widespread, with as many as half of river systems globally obstructed by at least one dam (Reidy Liermann *et al.,* 2012) and multiple dam projects currently planned or in development (Grumbine and Xu, 2011; Zarfl *et al.,* 2015). This infrastructure provides crucial socio-economic services such as water security, transportation, power, and flood control, but also induces a variety of ecological costs including decreased connectivity for aquatic organisms (Limburg and Waldman, 2009; Hall *et al.,* 2012; Cooney and Kwak, 2013).

Spatial planning of barriers has become an important area of focus for water resources planning and management (Doyle *et al.,* 2003; Kareiva, 2012). In some parts of the world like the Amazon River Basin (Finer and Jenkins, 2012) and the Mekong River Basin (Ziv *et al.,* 2012), the challenge is to examine when and where dam construction can provide the most benefits at the least cost to the environment (Brown *et al.,* 2009; Opperman *et al.,* 2015); while in other regions, spatial planning emphasizes barrier reengineering or removal, particularly in conjunction with aging infrastructure (Doyle *et al.,* 2008). These socially complex decisions can also be technically challenging because of the unique dendritic spatial structure of river systems (Eros *et al.,* 2012; Peterson *et al.,* 2013; Eros and Campbell-Grant, 2015).

A rapidly expanding body of literature describes application of spatial planning to inform these water resources decisions globally, and a wide variety of data, methods, and tools have been developed to inform these decisions. Our objective is to propose a repeatable, transparent procedure

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for spatial prioritization of barriers which restrict aquatic organism movement. We build upon an earlier review with a similar focus by Kemp and O'Hanley (2010), and particularly highlight more recent studies. This paper focuses on practical advice regarding seemingly simple decisions (e.g. which barrier data set, which focal species) because the cumulative influence of many small decisions can impact the outcome of barrier prioritization. The basic structure of this paper follows the proposed spatial planning steps and directs users to key references, data sources, techniques, tools, and online resources. We conclude with a discussion of emerging trends and issues in barrier prioritization and key opportunities for enhancing the body of knowledge.

A PROCEDURE FOR CONNECTIVITY BARRIER PRIORITIZATION

We use the term barrier prioritization to generally characterize the family of methods used to inform spatial planning decisions associated with riverine barrier addition and removal. Following Kemp and O'Hanley (2010), we use the term removal to refer to any mitigation action that reduces or eliminates the impact a barrier has on aquatic ecosystems, ranging from the repair or physical removal of barriers to the installation of fish passage facilities. Although we focus on an organism-centric view of connectivity (i.e. movement corridors), the basic principles and steps espoused here would also largely apply to non-organismal processes (e.g. sediment continuity, nutrient transport). We use the term barrier in the general sense of any discrete location where movement of an organism is inhibited, which could include road culverts, dams, water quality barriers, or physiological barriers (e.g. a velocity barrier at a recreational kayaking feature).

We compiled 46 peer-reviewed studies examining barrier prioritization (Table I). We excluded studies which presented methods without an application (e.g. Taylor and Love, 2003), examined theoretical landscapes (e.g. Padgham and Webb, 2010; Perkin *et al.,* 2013), or focused on process-oriented findings rather than management actions (e.g. Jaeger *et al.,* 2014; van Looy *et al.,* 2014a). We then synthesized a common set of barrier prioritization steps based on a qualitative review of these analyses. The authors also drew from experiences supporting these types of prioritization studies for federal, state, and non-profit organizations throughout North America. Based on this synthesis, we identified six steps common to barrier prioritization exercises (Table II). These steps apply to both removal and construction decisions; however, our analysis generally focuses on removal because only 4 of the 46 studies focused on barrier construction (but see Poff *et al.* (2015) for a call for getting engineers and ecologists involved early in the planning of river engineering projects). The sections that follow address each step individually and identify key references, data, techniques, and tools.

Step 1: Identify the scope of the analysis

The project objectives and spatial extent of a barrier prioritization guide the entire analysis. Choices made at this initial stage will influence data needs and techniques available in subsequent steps and dictate the range of outcomes that can be addressed in the analysis.

First, the geographic extent of the analysis needs to be defined. Because barrier prioritization typically includes evaluation of longitudinal connectivity along stream networks, this often involves the use of a watershed boundary that encompasses the stream(s) of interest. A variety of factors may influence the geographic scope of the analysis, including data availability, the distribution of target taxa, political mandates, and project funding, among others. The choice of watershed area should include consideration of legal and jurisdictional influences within the region (e.g. state boundaries, agency missions, Doyle *et al.,* 2003), as they may limit data access and/or publication of results. When considering both watershed size and the number of barriers to include in prioritization, it is important to understand their effect on the types of connectivity measures that are available and the subsequent prioritization methods that can be used.

Selection of focal taxa is the next crucial scoping decision. Will prioritization efforts target restoration or mitigation opportunities for individual species, a broader species assemblage, or a representative guild? What types of abiotic factors are most important to these taxa? For instance, stream connectivity requirements for anadromous/diadromous species vs. resident species (including potadromous species) could involve connectivity indices that uniquely emphasize the role of directionality (i.e. upstream only vs. upstream and downstream). Ideally, the connectivity requirements for target species/assemblages would involve a baseline understanding of movement capabilities within the stream system (e.g. O'Connor *et al.,* 2015) and/or physiological ability (e.g. Anderson *et al.,* 2012; Diebel *et al.,* 2014). Another key biotic consideration is the distribution of non-native or invasive species within the watershed of interest (Rahel, 2007; Jackson and Pringle, 2010). Non-native and invasive species distributions could be used to identify barriers that are currently preventing establishment of non-native species by limiting their dispersal (e.g. Novinger and Rahel, 2003; Peterson *et al.,* 2008; Fausch *et al.,* 2009) or barriers whose mitigation or removal would allow other harmful consequences, including the spread of diseases or undesirable genetic introgression (McLaughlin *et al.,* 2013).

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Table I. Barrier prioritization studies used to develop the procedure presented in this paper. Purpose of prioritization was classified generally as either restoration (i.e. removal, improvement, passage structures) or conservation (i.e. avoidance, construction). Barrier types were classified as either road crossings (e.g. culverts, bridges), dams (e.g. weirs, locks, and withdrawal structures), or natural (e.g. waterfalls, debris jams). Barrier permeability refers to the treatment of movement probability as either a binary (i.e. 0 or 1) or continuous variable. The prioritization approach was classified as presented in the text as scoring and ranking, stepwise scoring and ranking, scenario analysis, optimization, or complete enumeration

Citation	Purpose of prioritization	Barrier type(s)	Barrier permeability	Number of barriers	Prioritization technique
Andersen (2010)	Restoration	Road crossings	Continuous	80	Scenario analysis
Anderson *et al.* (2012)	Restoration	Road crossings	Continuous	156	Scoring and ranking
Bourne *et al.* (2011)	Restoration	Road crossings, Natural	Continuous	43	Stepwise scoring and ranking
Branco *et al.* (2014)	Restoration	Dams	Binary	29	Stepwise scoring and ranking
Brevé *et al.* (2014)	Restoration	Dams	n/a	2924	Scoring and ranking
Cote *et al.* (2009)	Restoration	Road crossings, Natural	Binary	16	Complete enumeration
Crook *et al.* (2009)	Restoration	Dams	Continuous	17	Scoring and ranking
Diebel *et al.* (2010)	Restoration	Road crossings	Continuous	192	Optimization
Diebel *et al.* (2014)	Restoration	Road crossings, Dams, Natural	Continuous	190	Stepwise scoring and ranking
Eros *et al.* (2011)	Restoration	Dams	Binary	14	Scoring and ranking
Finer and Jenkins (2012)	Conservation	Dams	Binary	151	Scoring and ranking
Grill *et al.* (2014)	Conservation	Dams	Binary	81	Scoring and ranking
Hicks and Sullivan (2008)	Restoration	Road crossings	Score	268	Scoring and ranking
Hoenke *et al.* (2014)	Restoration	Dams	Binary	5120	Scoring and ranking
Jager *et al.* (2007)	Restoration	Dams	Continuous	3	Complete enumeration
Karle (2005)	Restoration	Road crossings	Continuous	n/a	Scoring and ranking
King and O'Hanley (2014)	Restoration	Road crossings, Dams, Natural	Binary	6989	Optimization
Kocovsky *et al.* (2009)	Restoration	Dams	Binary	20	Scoring and ranking
Kuby *et al.* (2005)	Restoration	Dams	Binary	150	Optimization
Mader and Maier (2008)	Restoration	Dams, Natural	n/a	230	Scoring and ranking
Martin and Apse (2011)	Restoration	Dams, Natural	Binary	13 835	Scoring and ranking
Martin and Apse (2013)	Restoration	Dams, Natural	Binary	3883	Scoring and ranking
Martin *et al.* (2014)	Restoration	Dams, Natural	Binary	16 933	Scoring and ranking
McKay *et al.* (2013)	Restoration	Dams	Continuous	9	Complete enumeration
Melles *et al.* (2015)	Conservation	Dams	Binary	60	Scenario analysis
Mount *et al.* (2011)	Restoration	Road crossings	Binary	434 960	Stepwise scoring and ranking
Neeson *et al.* (2015)	Restoration	Road crossings, Dams, Natural	Binary, Continuous	238 760	Optimization
Null *et al.* (2014)	Restoration	Dams	Binary	44	Optimization
Nunn and Cowx (2012)	Restoration	Dams, Natural	Score	67	Scoring and ranking
O'Hanley (2011)	Restoration	Road crossings, Dams	Binary	125	Optimization
O'Hanley and Tomberlin (2005)	Restoration	Road crossings	Continuous	289	Optimization
O'Hanley *et al.* (2013)	Restoration	Road crossings, Dams, Natural	Continuous	130	Optimization
Oldford (2013)	Restoration	Road crossings, Dams	Continuous	556	Optimization
Paulsen and Wernstedt (1995)	Restoration	Dams	Continuous	16	Optimization
Pini Prato *et al.* (2011)	Restoration	Dams	Score	16	Scoring and ranking
Poplar-Jeffers *et al.* (2009)	Restoration	Road crossings	Continuous	120	Scoring and ranking
Quiñones *et al.* (2014)	Restoration	Dams	Binary	24	Scoring and ranking
Schick and Lindley (2007)	Restoration	Dams	Continuous	12	Scenario analysis

(Continues)

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Table I. (Continued)

Citation	Purpose of prioritization	Barrier type(s)	Barrier permeability	Number of barriers	Prioritization technique
Segurado *et al.* (2013)	Restoration	Dams	Binary	29	Stepwise scoring and ranking
Walters *et al.* (2012)	Restoration	Dams	Continuous	41	Scenario analysis
Wu *et al.* (2013)	Restoration	Road crossings, Dams	Continuous	1523	Optimization
Wu *et al.* (2014)	Restoration	Road crossings, Dams	Continuous	8162	Optimization
Xiankun (2014)	Restoration	Dams	Binary	1358	Scoring and ranking
Zheng *et al.* (2009)	Restoration	Dams	Binary	139	Optimization
Zheng and Hobbs (2013)	Restoration	Dams	Binary	139	Optimization
Ziv *et al.* (2012)	Conservation	Dams	Binary	27	Complete enumeration

The final scoping consideration is to identify the types of management actions that will be considered as options. Will alternatives to full passage, such as partial passage (e.g. fish ladders), be considered to allow movement for certain species and/or life stages (McKay *et al.,* 2013; Rahel, 2013)? Will barrier subtraction, addition, or both be considered? Although barrier removal is often the focus of prioritization, riverine barriers will likely be added in certain parts of the world to meet increasing societal demands for water and energy (Jager *et al.,* 2015; Melles *et al.,* 2015). Prioritizing addition involves identifying locations for new barriers that meet underlying goals (e.g. increased energy supply) while attempting to minimize ecological impact to streams (Kemp and O'Hanley, 2010; Jager *et al.,* 2015). Other attributes of barriers, such as barrier purpose and ownership, can provide information on social importance and function of barriers.

Table II. Overview of the proposed protocol for aquatic connectivity barrier prioritization

Step	Description and key guiding questions
1	Identify the scope of the analysis •Who is the decision-maker? Are many groups involved in the decisions? •Is the focus restoration (i.e. barrier improvement or removal) or conservation (i.e. barrier construction or invasive species prevention)? •What are the objectives for prioritization (e.g. single v. multiple species, anadromous v. resident, native v. invasive, organism-focus v. sediment continuity)? •Are non-connectivity outcomes also being considered (e.g. dam safety)? •What are the spatial limits of the analysis? •Are there scope/legal boundaries (e.g. political, jurisdictional)? •What types of barriers are being addressed (e.g. culverts, dams, withdrawals)? •What are the alternatives under consideration (e.g. do nothing, removal, fish ladders, bypasses, screens, culvert types)?
2	Develop a geospatial database •What anthropogenic barriers are being addressed? •What natural barriers are being used? •What measure of habitat quantity is pertinent (e.g. length, area, volume)? •Is habitat quality a concern? How will it be quantified? •How will passage rates be estimated at each barrier (i.e. binary, rules, regression, FishXing, judgment)? •How will project costs be computed (e.g. site-by-site estimates, regression)?
3	Predict connectivity for the watershed •How will connectivity be computed? What indices will be applied? •If multiple indices are used (i.e. for multiple species), how will these metrics be combined into an overall assessment?
4	Compute costs and benefits of alternative scenarios •How many scenarios are possible (i.e. how many barriers are there)? How many scenarios will be investigated? •What techniques will be applied to assess costs and benefits for each? •What expertise and computational resources are available to the team?
5	Summarize information for decision-making and take action •What is the best way to present model outcomes to decision makers (e.g. maps, trade-off plots, ranking tables, etc.)? •Should information be summarized as an online decision support tool to reach a broad array of partners and interested parties?
6	Don't forget post-project actions •Who is leading monitoring and adaptive management? •Are regional and national data sets being updated following barrier improvement or construction (e.g. National Inventory of Dams; USGS DRIP, Duda *et al.,* 2015)?

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For instance, primary dam purpose has been utilized to identify dams currently used in hydroelectric power generation, flood control, and municipal water supply that may be unlikely candidates for dam removal and are not considered in some dam removal prioritizations (e.g. Kocovsky *et al.,* 2009; Hoenke *et al.,* 2014). Determining which barriers to include in prioritization, and the available set of attributes for those barriers, will inform subsequent prioritization steps.

Step 2: Develop a geospatial database

After preliminary scoping, potential data needs should to be assessed. Based on data needs of previous prioritization efforts (Table I), we identified six general categories of data common to most barrier prioritizations: (i) a spatial model of stream networks, (ii) anthropogenic barriers, (iii) natural barriers, (iv) habitat quantity and quality, (v) barrier passability estimates, and (vi) removal cost estimates. This section describes these categories, identifies potential national and regional data sources (Table III), and provides recommendations for developing project-specific data (Table IV).

A consistent and accurate spatial model of a watershed and stream network provides the backbone of a successful prioritization effort. A spatial model of the stream network helps pull together disparate datasets into an analytical

Table III. Watershed scale data resources for barrier prioritization

Type of data	Key national and regional data sets	Select references
Stream network properties	NHDPlusV1	http://www.horizon-systems.com/ NHDPlus/NHDPlusV1_home.php
	NHDPlusV2	http://www.horizon-systems.com/ NHDPlus/NHDPlusV2_home.php
	NHD High Resolution	http://nhd.usgs.gov/data.html
Anthropogenic barriers	GRAND Data set	Lehner *et al.* (2011)
	National Anthropogenic Barrier Dataset (2012): large dams, restricted to U.S. federal employees	http://dx.doi.org/10.5066/F7VX0DFG
	USGS Spatial Features Registry: road crossings, bridges, dams, removed dams	https://www.sciencebase.gov/catalog/item/ 55fafaf5e4b05d6c4e501b81
	National Inventory of Dams: large dams, restricted to U.S. federal employees	http://nid.usace.army.mil
	California Fish Passage Assessment Dataset: 'salmonid barriers', regional	http://dx.doi.org/10.5066/F7X06527
	Southeast Aquatic Connectivity Assessment Project (SEACAP): dams	Martin *et al.* (2014), http://maps.tnc/org/seacap/
	National Hydrography Database Plus: dams, lock chambers, gates	http://www.horizon-systems.com/nhdplus
	National Hydrography Database Hydrography Features: dams, weirs, reservoirs, lock chambers	http://nhd.usgs.gov/userGuide/Robohelpfiles/ NHD_User_Guide/Feature_Catalog/ Hydrography_Dataset/ Complete_FCode_List.htm
	North Atlantic Aquatic Connectivity Collaborative: culverts	https://streamcontinuity.org/about_naacc/ index.htm
	Northeast Aquatic Connectivity Analysis: dams	Martin and Apse (2011)
	Chesapeake Fish Passage Prioritization: dams	Martin and Apse (2013)
	Alaskan Culvert Assessment: culverts	http://www.adfg.alaska.gov/ index.cfm?adfg=fishpassage.databaseAlaska
	Great Lakes Connectivity: dams, road-stream crossings	Neeson *et al.* (2015), https://greatlakesconnectivity.org/
	SalmonScape: dams, culverts, other barriers	http://apps.wdfw.wa.gov/salmonscape/map.html
	CanFishPass: fishways	Hatry *et al.* (2011)
Natural barriers	Spatial Features Registry: waterfalls	https://www.sciencebase.gov/catalog/item/ 55fafaf5e4b05d6c4e501b81
	World Waterfall Database	http://www.worldwaterfalldatabase.com/
	National Hydrography Database Plus: rapids, spring seeps, waterfalls	http://www.horizon-systems.com/nhdplus
	National Hydrography Database Hydrography Features: rapids, sinks/rises, springs/seeps, waterfalls	http://nhd.usgs.gov/userGuide/Robohelpfiles/ NHD_User_Guide/Feature_Catalog/ Hydrography_Dataset/Complete_FCode_List.htm

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Table IV. Summary of techniques for estimating passability and project costs. A comparable table was presented by Kemp and O'Hanley (2010). Here, we present a simplified version directing readers to examples and applications

Barrier property	Families of methods	Select examples
Empirically derived passage rates	Direct observation tracks the movement of individual organisms as they move around a given barrier.	Direct observation and filming; Hydroacoustic sonar (Lucas and Baras, 2001); Passive integrated transponder (Bunt *et al.,* 2012)
	Indirect observations of passage rates may be inferred from other empirical, monitoring data sets.	Presence/absence (Meixler *et al.,* 2009); Density (Pepino *et al.,* 2013); Capture–mark–recapture (Norman *et al.,* 2009)
	Genetic methods are emerging, which can be applied to estimate or infer passage rates.	Genetic connectivity (Hughes *et al.,* 2013); eDNA (Farrington and Lance, 2014)
Analytically derived passage rates	Rule-based methods are common for logically deriving passability by coupling physical attributes of a site and associated hydraulics with data on the physiological capabilities of a species.	FishXing (Furniss *et al.,* 2006); Regional rules (Anderson *et al.,* 2012; Diebel *et al.,* 2014)
	Statistical models are commonly derived by calibrating physical surveys of barriers with an empirical estimate of passage (commonly presence/absence or density data).	Boosted regression trees (Januchowski-Hartley *et al.,* 2014); Bayesian networks (Andersen, 2010)Meta-analysis (Noonan *et al.,* 2011)
	Individual-based models couple detailed hydrodynamic simulation with behavioural and cognitive data to provide theoretical movement patterns of individual 'virtual fish.'	Eulerian–Langrangian Agent Methods (Goodwin *et al.,* 2014)
	Professional judgments of experts familiar with sites and taxa provide the simplest form of passability estimates.	Single estimates for all barriers (Cote *et al.,* 2009); Expert panel elicitation (McKay *et al.,* 2013)
Cost	Site-by-site methods work with engineering and economic teams to develop unique estimates for local constraints.	Standard U.S. Federal cost estimation procedures (McKay *et al.,* 2013)
	Simple rules apply blanket estimates for all barriers of a particular type (e.g. $10 M/dam) or rules developed by infrastructure organizations (e.g. Transportation Departments).	Per unit cost estimates (e.g. $/foot of bypass, Mader and Maier, 2008; $/unit length of culvert, Neeson *et al.,* 2015)
	Regression models can be developed for regional application based on costs of prior barrier improvements.	Regression with dam height (Neeson *et al.,* 2015); Multivariate regression based on dam height, length, purpose, and type (Zheng *et al.,* 2009)
	Economic benefits forgone can be computed based on lost economic services (monetary or non-monetary) associated with hydropower, water supply, recreation, or other outcomes.	Water storage and hydropower generation capacity (Kuby *et al.,* 2005)

framework by building spatial relationships between barriers, habitat measures, and the stream network itself. A stream network can be identified using mapped layers provided at a national scale (e.g. the high resolution 1:100 000 scale National Hydrography Dataset Plus, NHDPlus, McKay *et al.,* 2012) or delineated on a project-by-project basis. National datasets provide a consistent stream model for the conterminous U.S. and may also have a number of habitat quality measures and other data available within the datasets themselves.

Accurately locating and compiling physical characteristics of each anthropogenic barrier on the stream network is an essential step for prioritization. Anthropogenic barriers include large dams, low-head dams, weirs, road-stream crossings, reservoirs, stream diversions, bridges, and other barriers of interest to a particular analysis (e.g. water quality barriers). For large barriers such as dams, national and regional efforts have compiled consistent datasets with many descriptive attributes about each feature (Table III), yet many of these datasets have restricted access because of agency or even national security policies and may support only a limited set of attributes. However, the spatial resolution of these national dam datasets is such that some manual reconciliation with high-resolution stream networks is often required. Information about smaller barriers, such as road-stream crossings and low-head dams, is becoming more readily available, but these data remain challenging to compile at large spatial scales (Januchowski-Hartley *et al.,* 2013).

Although infrequently included in prioritization efforts, natural barriers such as waterfalls, estuary sedimentation, beaver dams, and debris jams can influence the outcome of connectivity analyses (Cote *et al.,* 2009). These barriers are natural components of the landscape, are often transient, and can be advantageous for some species (e.g. prey refugia, Cooney and Kwak, 2013). Many projects currently omit natural barriers because of a lack of watershed-wide, readily available data. The U.S. Geological Survey is currently developing a standardized national waterfall dataset (citation forthcoming in the Spatial Features Registry).

Barrier prioritizations often utilize information about the quantity, quality, and spatial distribution of habitat within

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the focal watershed (see Step 3 below). In the majority of studies, river quantity is usually quantified using length (O'Hanley and Tomberlin, 2005; Cote *et al.,* 2009; Kocovsky *et al.,* 2009; McKay *et al.,* 2013; Segurado *et al.,* 2013; Diebel *et al.,* 2014; King and O'Hanley, 2014), although surface area (Brevé *et al.,* 2014) or volume (Grill *et al.,* 2014) has also been used to account for variation in width and depth of a river. Few studies address habitat quality beyond a general notion of the expected home range of a focal taxa. Quality could be incorporated into these analyses through pre-existing mapping projects (e.g. the National Fish Habitat Partnership, the Environmental Protection Agency's StreamCat, the National Stream Internet Project), surrogates for quality (e.g. mining density, land use), or mechanistic variables (e.g. stream temperature via NorWest Stream Temp). Future barrier prioritizations should seek to include these measures of quality as data sets become increasingly available.

Large and small barriers differentially affect the ability of an organism to move, and no two barriers in a watershed perform identically. The proportion of organisms passing a structure is typically summarized as a passage rate (i.e. passage efficiency or barrier passability). Ideally, each barrier would have a unique site-specific value of passability, and some regional analyses are building these types of databases (e.g. SalmonScape, CAFishPass, North Atlantic Aquatic Connectivity Collaborative). However, passage rates must often be estimated for many barriers within a watershed, and a site-by-site analysis is often cost-prohibitive. Depending on the scope of the analysis, a binary view of passage may be sufficient (i.e. pass or no pass) or a continuous view of passage may be required (i.e. a rate between 0 and 100%). Table I summarizes the passability approach used by each of the studies reviewed here. Kemp and O'Hanley (2010) provide a thorough review of strategies for assessing passability using a variety of techniques and methods, and Table IV summarizes general approaches for quantifying passability. At large spatial scales common to barrier prioritizations, simple analytical techniques are often preferred to rapidly predict passage (e.g. simple rules involving barrier properties such as height).

The final element of the geospatial database is a cost estimate of barrier removal at each site. For small numbers of barriers, this may consist of a site-by-site analysis using engineering economics (e.g. McKay *et al.,* 2013). However, for large watersheds, cost estimations are often conducted using simple rules (e.g. $/foot of fish ladder, Mader and Maier, 2008) or regression models based on prior dam removals (e.g. Neeson *et al.,* 2015). Some studies have also incorporated economic benefits foregone (Kuby *et al.,* 2005) and invasive species control required because of barrier removal (Zheng *et al.,* 2009). To date, no studies have included economies of scale associated with coordinating multiple barrier removal projects. Table IV also summarizes some techniques for barrier removal cost estimation.

Step 3: Predict connectivity for the watershed

The past two decades have seen a rapid expansion of efforts to incorporate measures of longitudinal connectivity into barrier prioritization. A number of localized metrics have been applied, such as the presence or number of downstream barriers (Karle, 2005; Kuby *et al.,* 2005; Mount *et al.,* 2011; Hoenke *et al.,* 2014), presence of upstream barriers (Taylor and Love, 2003; Hicks and Sullivan, 2008; Anderson *et al.,* 2012), distance to the river mouth (Kocovsky *et al.,* 2009), and probability of passage to river mouth (Crook *et al.,* 2009; Nunn and Cowx, 2012). With the increased recognition of the importance of metrics to quantify riverscape-scale connectivity (Jansson *et al.,* 2007; Beechie *et al.,* 2010; Eros and Campbell-Grant, 2015) and progress in technology and analytical techniques, researchers are increasingly incorporating systemic indices of connectivity into prioritizations (e.g. Cote *et al.,* 2009; Pini Prato *et al.,* 2011; Segurado *et al.,* 2013; Diebel *et al.,* 2014). Not all metrics are appropriate or realistic to use in every prioritization context, however, with the choice depending on the objectives of the analysis and data available.

Here, we review three dimensions common to most riverscape-scale connectivity metrics: fragmentation, connectivity, and distance. Finally, we look at applications of graph theory and geographic information systems (GIS) for quantifying connectivity.

Many connectivity metrics are based upon coincidence probability and cumulative passability between fragments, which can be further subdivided into those metrics reflecting diadromous and potamodromous life histories. These metrics usually incorporate a measure of fragmentation, or degree of landscape division. Given a river divided by a number of barriers, the fragmentation of the river can be quantified as the probability that two randomly chosen points fall within the same river fragment (i.e. coincidence probability; Jaeger, 2000; Pascual-Hortal and Saura, 2006). In terms of animal movement, this metric can be conceptualized as either the probability that an individual can move freely between any two random locations or the probability that any two individuals can find each other from two random locations.

To calculate cumulative passability between fragments, a connectivity term can be introduced to summarize pairwise connectivity values (e.g. the Dendritic Connectivity Index, Cote *et al.,* 2009), which yields a single metric for each fragment or the proportion of passability-weighted river network available from a focal fragment. These segmental metrics may then be combined to reflect the total connectivity of an entire river system (e.g. probability of connectivity, Saura

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and Pascual-Hortal, 2007 and the potamodromous Dendritic Connectivity Index, Cote *et al.,* 2009). Alternatively, to arrive at a metric that reflects the needs of a diadromous life history, pairwise connectivity can be calculated only between river segments and the system sink (i.e. the ocean or watershed pour point, diadromous Dendritic Connectivity Index, Cote *et al.,* 2009).

A distance dimension reflecting the dispersal ability of fish is important to functional connectivity (Radinger and Wolter, 2015) and can be incorporated into connectivity metrics using a dispersal kernel. Diebel *et al.* (2014), for example, apply an inverse distance weighting function as a multiplier for each pairwise connection between fragments. An alternative is incorporating a measure of topological distance, or the distance measured in network elements between two fragments (Pascual-Hortal and Saura, 2006; van Looy *et al.,* 2014b).

Eros *et al.* (2012) introduced the use of spatial graphs for the topological analysis of stream networks. A number of graph theoretical metrics quantify the importance of individual fragments for the overall connectivity of the system. For example, betweenness-centrality identifies the topological 'center' of a river network based on how often a fragment appears on the path between all pairs of segments (Altermatt, 2013). For a thorough examination of a number of graph theoretical metrics applied to rivers, see Malvadkar *et al.* (2015) and for a review of recent applications of graph theory to aquatic ecosystems see Saunders *et al.* (2015).

As prioritization involves simulation of barrier removal, iterative re-calculation of connectivity metrics is required which can be computationally intensive. Graph theory and geographic information systems (GIS) are powerful analytical tools that can help calculate river connectivity metrics. McKay *et al.* (2013) construct passage and adjacency matrices and demonstrate that simple matrix multiplication can calculate the cumulative passage rate between any two nodes. Oldford (2013) demonstrates modification of an open-source GIS toolset, FIPEX (Fisheries and Oceans Canada, 2010), to generate adjacency matrices as well as summarize the river habitat available between barriers, calculate connectivity indices, and call upon optimization software. FIDIMO, another open-source GIS toolset can be used to model fish dispersal on river networks (Radinger *et al.,* 2014). The U.S. Forest Service has developed a similar GIS toolkit to facilitate barrier prioritization analyses, the Crossing Assessment Decision Support System (CADSS, http://cmi.vt.edu/Articles/art_CADSS.html). GIS tools continue to be developed which translate geographic databases (Step 2) into connectivity indices (Step 3) to facilitate barrier prioritization studies (e.g. Hoenke *et al.,* 2014).

Step 4: Compute costs and benefits of alternative scenarios

Although the need for systematic river restoration planning is well-acknowledged (Doyle *et al.,* 2003; Jansson *et al.,* 2007; Beechie *et al.,* 2010), the number of barriers present on typical river systems creates substantial challenges for efficiently allocating limited time and effort by selecting from an extremely large number of alternatives. For instance, the problem of selecting the best 5 projects (*r*) among 200 possible projects (*n*) requires choosing from 2.5e + 9 possible alternatives (i.e. $n!/(n-r)!\,r!$). Adding to the task, dendritic ecological networks are more strongly connected than terrestrial networks, typically having only one path between any two network locations (Padgham and Webb, 2010; Eros *et al.,* 2012; Peterson *et al.,* 2013), which leads to strong spatial interdependence between individual projects (O'Hanley and Tomberlin, 2005; Segurado *et al.,* 2013).

As an illustration, Figure 1a represents an extremely simple scenario: only two barriers are present, costs of projects are assumed equal, passabilities are assumed bidirectional and binary, and systemic connectivity is assessed as the proportion of passability-weighted river network connected to and from the system outlet. Consider only one project option at each barrier—full repair from zero to 100 percent passability. If only one barrier is to be selected for removal, barrier B is the better candidate for anadromous life histories. Although barrier A has more of the river network upstream, removal of this barrier would result in no net benefit because of the presence of barrier B. The estimated benefits of removing either barrier change depending on the presence of the other. By introducing a third barrier, C (

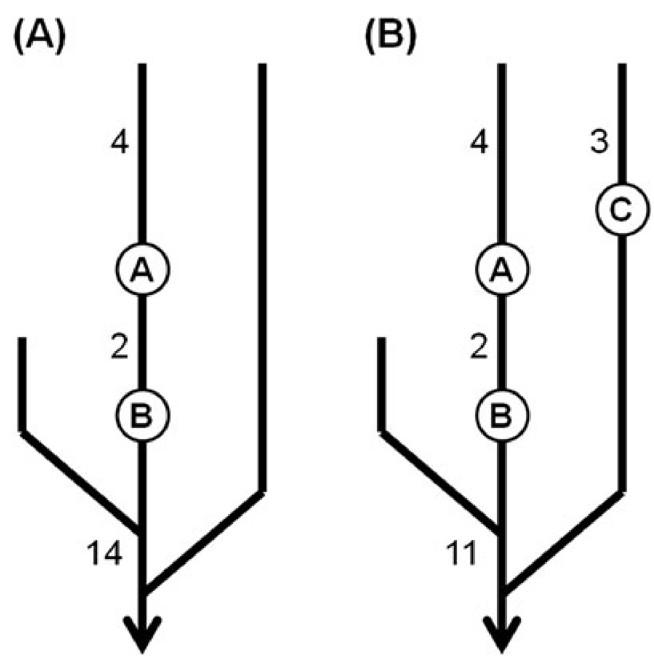

Figure 1. Hypothetical barrier removal scenarios for a simple river network demonstrating: (a) dependency between actions and (b) lack of nestedness in solution sets. See text for explanation of the two scenarios

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Figure 1b), it becomes apparent that if one barrier is to be selected, barrier C would be the best choice yielding a connectivity gain of 3 units. However, if two barriers are to be repaired, the best choice would be barriers A and B, yielding a connectivity gain of 6 units. The benefits of removing barriers A and B are greater than the sum of the estimated benefit of each taken individually and are thus non-additive. Furthermore, the most efficient decisions for repairing one versus two barriers are non-nested, as barrier 'C' does not appear in the decision set associated with removing two barriers. This leads to two important considerations for decision makers: (i) the choice of effort (e.g. budget) can impact the efficiency of restoration efforts (Neeson *et al.,* 2015) and (ii) evaluating costs and benefits of individual projects is typically a task distinct from evaluating multiple projects at once.

The ultimate objective of barrier prioritization is to identify a cost-effective solution for any budget or desired degree of connectivity. Efficient solutions (i.e. Pareto-optimal) provide the most connectivity for any level of investment and the least cost for any level of connectivity (Figure 2). From the literature, we identify three general classes of methods to select a solution set (i.e. a portfolio of barriers for removal): complete enumeration, scoring and ranking, and optimization. Importantly, not all methods result in optimal solutions (King and O'Hanley, 2014).

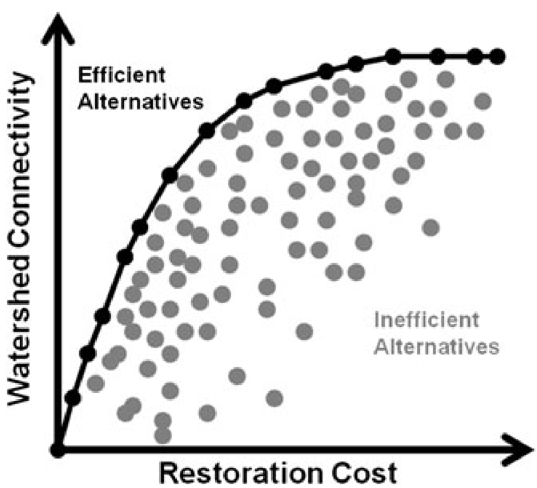

Figure 2. Hypothetical outcomes of costs and benefits for potential barrier removal scenarios. The overarching objective of a barrier prioritization study is to identify efficient solution sets. These actions provide the most connectivity for any level of restoration investment and the least cost for any level of connectivity. Notably, costs and benefits are used broadly to imply any form of cost or benefit associated with restoration (e.g. time, funding, carbon emissions, social capital). While most barrier prioritizations emphasize finding optimal solutions relative to connectivity and monetary cost, sub-optimal plans may sometimes be more socially or institutionally preferable (see section on 'Balancing strategy and opportunity').

Without computational constraints, the obvious approach is to examine all potential combinations of barrier removals. From this 'complete enumeration,' the optimal set may then be selected. This method provides the maximum amount of information for decision-makers by presenting efficient alternatives relative to all other options (McKay *et al.,* 2013). However, this method is only practical for small sets of barriers. For instance, if the only options are to remove or leave a barrier and there are 40 barriers, there are 1.1e + 12 potential combinations of actions (2^{40}).

Scoring and ranking entail assigning each option a score based on the associated costs and benefits and sorting that list to identify top projects (e.g. Kocovsky *et al.,* 2009; Martin and Apse, 2011; Segurado *et al.,* 2013). This method has the advantages of being computationally efficient, flexible, transparent, and does not require a high degree of mathematical or technical expertise, nor specialized software. Despite the relative simplicity of scoring and ranking, the calculation of costs and benefits can be rigorous. The primary drawback of the scoring and ranking approach is that it is static—costs and benefits for a given project are calculated once at the outset and remain static even when considered along with other simultaneous projects. Thus, spatial interdependence of costs and benefits is not accounted for which can lead to inefficient outcomes (O'Hanley and Tomberlin, 2005). The majority of these applications function as single barrier rankings. However, a parallel analytical approach is for a prioritization team to develop sets of barriers for consideration and analyse and rank each scenario independently. This format can take into account dependencies between multiple barriers, but large numbers of scenarios cannot feasibly be executed. A third form of scoring and ranking applies a 'greedy' algorithm to account for spatial interdependence by re-scoring costs and benefits after a project is selected. This stepwise scoring and ranking is an iterative approach to selecting more than one project in which an ordered list based on scores of costs and benefits is created, the best project is selected (usually the single top priority), the scores of all other projects are re-calculated, a new ranked list is created, and the process is repeated. Although this technique addresses the interdependence of projects, priorities are always nested and the globally optimum solution cannot be guaranteed (Cormen, 2009; O'Hanley *et al.,* 2013).

Optimization can be used to find efficient solutions when multiple barriers are selected and spatial interdependence between costs and benefits is a factor (see Kemp and O'Hanley, 2010 for a summary). When the number of barriers is too high for complete enumeration, sophisticated optimization models and algorithms can be applied to efficiently search the solution space (Kuby *et al.,* 2005; O'Hanley and Tomberlin, 2005; Zheng *et al.,* 2009; O'Hanley, 2011; O'Hanley *et al.,* 2013). Optimization is

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advantageous in that it provides techniques to identify efficient sets of projects from an extremely large number possible alternatives. A second advantage is that optimization can account for spatial interdependence of projects. Optimization does, however, require specialized mathematical and programming expertise, which can serve as a feasibility barrier to some teams.

`On its face, computing costs and benefits of barrier scenarios (Step 4) seems simple relative to building a geospatial database (Step 2) and computing connectivity indices (Step 3). However, the large number of barriers in a typical watershed creates a numerically large problem, which often requires complex mathematical methods. Ultimately, the prioritization method chosen is often dictated by logistical constraints such as the number of barriers, availability of computational resources, expertise of the analysis team, and even opportunistic actions.

Step 5: Summarize information for decision making and take action

Ultimately, the output from prioritization analyses must be distilled into a usable format to support decision making (Shim *et al.,* 2002). The format and presentation of model output deserve careful consideration, as there is a fine line between providing enough information for informed decision making and information overload. Given the wide variety of graphical and tabular output options available today it may be tempting to err on the side of over-informing, but overwhelming decision-makers with outputs can cause confusion, loss of confidence in the model as an informative tool, and ultimately the decline of support for developing additional prioritization tools. At the opposite extreme it may seem efficient to present a decision maker with a simple numbered list or map of barrier replacement options, but lack of understanding of the nuances of a particular prioritization approach can lead to decisions that are controversial (e.g. viewed as bias), ineffective (e.g. far from optimal), or have unintended consequences (e.g. do not adequately consider available information to inform decision-making).

Many barrier prioritization teams are using online tools to overcome the many technical challenges highlighted here (i. e. geospatial data compilation, connectivity calculations, and numerical solution methods). In the U.S., regional connectivity analyses in the Northeast (Martin and Apse, 2011), Chesapeake Bay (Martin and Apse, 2013), Southeast (Hoenke *et al.,* 2014; Martin *et al.,* 2014), and Great Lakes (Neeson *et al.,* 2015) are all using online models and tools to effectively facilitate barrier prioritization involving multiple local, state, and federal partners. These tools create an interactive environment, where multiple agencies and groups can coordinate and select sets of projects based on their missions and objectives. National scale tools such as the Geospatial Fisheries Information Network (GeoFIN) and the Environmental Risk Assessment and Management System (eRAMS) are also beginning to incorporate these techniques. However, at the time of writing, no national-scale tool facilitates large-scale barrier prioritization.

When pressed to prioritize among projects, it is tempting for decision makers to turn to models simply as a way to generate lists of barriers for remediation. Using prioritization models in this limited manner may inadvertently discredit the models when their output does not align with societal, political, or economic factors that also weigh heavily in the decision making process (Lynch *et al.,* 2015). Also lost is the important aspect of using the model in the decision support process to better understand the issues at hand and to inform multiple alternative solutions (Shim *et al.,* 2002). Prioritization models are very useful for informing restoration and mitigation decisions, but the most successful prioritizations involve decision-makers and technical experts working with models and other available information to make the most informed decision possible.

Step 6: Do not forget post-project actions

Significant time and resources are invested in selecting, planning, and implementing barrier removal projects. The physical removal of a barrier is often seen as the crowning achievement, attracting significant local, regional, and in some cases even national attention. However, as the spotlight fades, the critical work of implementation and effectiveness monitoring is just beginning. Implementation monitoring sets the context for what benefits can be expected of a given project. For example, if a road crossing is modified to improve upstream fish passage it is critical to determine if the crossing modifications were completed according to specification; only properly executed modifications have the potential to deliver desired outcomes. The design of effectiveness monitoring depends on desired outcomes, but generally can be divided into individual project or programmatic level monitoring (Chelgren and Dunham, 2015). Regardless, effectiveness monitoring is needed to provide feedback for the improvement of prioritization models (e.g. better passage rates, connectivity indices, cost data, etc.).

An often overlooked activity is updating geospatial databases as the landscape changes over the course of barrier removal or addition. National scale dam removal databases are currently maintained or in development by American Rivers and the U.S. Geological Survey (via the Dam Removal Information Portal, DRIP, Duda *et al.,* 2015). Furthermore, datasets like the National Inventory of Dams and National Hydrography Dataset should be regularly updated to reflect new features (or removal of old features).

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The final step involves repeating the prioritization process! Assuming barriers are being added or removed from the landscape, barrier prioritization is by nature an iterative exercise. Sequential decisions are required as funding increases and decreases for these activities. Furthermore, the decision context changes over time as infrastructure conditions change, non-traditional partnerships form (e.g. Transportation Departments and whitewater boaters), the public becomes increasingly interested in dam removal, and the restoration community demonstrates the outcomes of dam removal (Doyle *et al.,* 2003).

OPPORTUNITIES FOR IMPROVING BARRIER PRIORITIZATION

In approximately the last decade, barrier prioritization has matured from an incipient field of conservation studies to a well-developed family of methods, tools, databases, and practitioners. However, barrier prioritization requires a team to overcome a variety of technically sophisticated ecological, numerical, and social challenges (e.g. complex migratory life histories, network analysis, optimization, multi-objective decision-making). Here, we identify key research opportunities to continue advancing the practice of barrier prioritization.

Availability of standardized data sets

We have emphasized the importance and utility of an accurate geospatial database, but these data can be challenging to compile. At the time of writing, there exists no single data set for barriers with unified locations because of different objectives for data compilation. For instance, the National Inventory of Dams was constructed for dam safety purposes (not ecosystem restoration) and explicitly targets dams with potential flood risks. This data set excluded small barriers such as mill dams and weirs, in part for logistic reasons, but in a study of the Apalachicola–Chattahoochee–Flint watershed, Ignatius and Stallins (2011) found that the NID was a 22 fold underestimate of man-made reservoirs in the basin (i.e. the NID has 1113 dams, and the authors identified over 25 362 dams). Furthermore, some data sets have restricted sharing requirements because of proprietary reasons or national security risks (e.g. to electricity production or flood safety). Standardized data sets also provide a consistent basis for comparison of prioritizations at large spatial scales. For instance, metrics assessing the quantity of connected habitat may differ if alternate streamline data sets are used (e.g. NHDPlus v. delineated via GIS). National datasets also typically contain unique identifiers, which can then easily link data back to the dataset updates following barrier removal or construction. In the U.S., the NHDPlusV2 provides a consistent spatial framework into which data sets on anthropogenic and natural barriers and habitat quality and quantity are being compiled. Notably, the scale of the dataset (i.e. 1:100 000 v. 1:24 000) can also influence which barriers are included or excluded.

Validating connectivity indices

The majority of connectivity indices are based on theoretical models combining passage rates for multiple sites to quantify the cumulative probability of accessibility of a given point in a watershed. Most of these indices have not been rigorously tested against field observations of species distributions (Kemp and O’Hanley, 2010), but see Perkin and Gido (2012) and Samia *et al.* (2015). Importantly, the relevance of a given metric depends upon the life histories (e.g. diadromous v. potamodromous), habitat preferences, and swimming abilities of particular taxa, and verification of these indices for one species does not necessarily imply transferability to others. Application of multiple indices at a site (e.g. Malvadkar *et al.,* 2015) and rigorous field verification would provide confidence that the theoretical basis for connectivity models was appropriate. Furthermore, validation from small to large spatial scales is important to understand dependency between locations with sequential passage as fatigue or stress of migration could be an important consideration (Kemp and O’Hanley, 2010).

Structural vs. functional connectivity

A fundamental assumption of most barrier analyses is that spatial structure is predictive of ecological function. The vast majority of barrier prioritizations use spatial metrics quantifying stream network topology and habitat size, but the desired outcomes of restoration are ecological functions such as individual movement (e.g. van Looy *et al.,* 2014a, 2014b), persistence of a metapopulation (e.g. Schick and Lindley, 2007), or gene flow between populations (e.g. Hughes *et al.,* 2013). A second crucial form of validation would investigate the relationship between structural spatial connectivity metrics and functional outcomes (Saunders *et al.,* 2015).

Quantifying and managing uncertainty

Passage rates often contain significant measurement uncertainty (Noonan *et al.,* 2011), and hydrologic fluctuation and individual variation in physiology also introduce ranges of potential passage rates (Anderson *et al.,* 2012). Furthermore, infrastructure projects often contain significant uncertainties in cost estimates (e.g. Ansar *et al.,* 2014). This variability in both costs and benefits of restoration introduce uncertainties to connectivity analyses, which can be large relative to the difference in optimal plans (McKay *et al.,* 2013). Simulation provides a mechanism to examine

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uncertainty bounds, but this approach introduces a computational hurdle with large numerical optimization problems. A key research area involves the role of uncertainty in identification of optimal barrier removal sets. For instance, is a near-optimal solution set within the range of uncertainty expected in the model? Given these open questions, practitioners should consider the role of uncertainty in analyzing the outcome of barrier prioritizations.

Simple tools for informing complex decisions

As discussed, online tools are emerging for regional barrier prioritizations, which conduct complex analyses and provide users with easily interpretable results (e.g. Martin and Apse, 2011; Martin and Apse, 2013; Martin *et al.,* 2014; Neeson *et al.,* 2015; USFWS, 2015). Barrier decision-making is a complex multi-objective problem contingent on ecological benefits, restoration costs, infrastructure condition, and many other variables (Doyle *et al.,* 2003; Hoenke *et al.,* 2014). Researchers are challenged with providing intuitive, simple tools to inform these decisions, while maintaining complexity in this decision-making environment (Stirling, 2010).

Balancing strategy and opportunity

Strategic barrier removal via rigorous, interdependent analysis has proven to provide significantly more efficient solutions than simple scoring and ranking procedures (O'Hanley and Tomberlin, 2005). However, in practice, barrier removal is often conducted on an ad hoc, opportunistic basis when some combination of a willing dam owner, lack of local controversy, a strong partner with recreational or dam safety concerns, or other reasons presents a tractable project (Pohl, 2002). In many cases, opportunistic barrier removal may, in fact, be preferable given the complexities of social and economic constraints. Decision-makers and restoration practitioners will need to balance long-term strategic planning with opportunistic actions to achieve the broader goals of connectivity. As barriers are removed, reprioritization will be a necessary step in this process, and all barrier prioritizations should be considered periodically as watershed conditions, stakeholder values, and infrastructure conditions shift over time.

CONCLUSION

Water resources and transportation infrastructure such as dams and culverts provide countless socio-economic benefits; however, this infrastructure can also disconnect the movement of organisms, sediment, and water through river ecosystems. Trade-offs associated with these competing costs and benefits occur globally with developing nations addressing the problem through the lens of barrier addition (e.g. dam and road construction) and developed nations through the lens of barrier removal and aging infrastructure. From the standpoint of environmental and social sustainability, getting dams 'right' is one of the great conservation and development challenges of the next decade (Kareiva, 2012; Jager *et al.,* 2015).

The scientific need for barrier prioritization methods is easily demonstrated by the diversity of groups investing in this topic ranging from the non-profit community (e.g. The Nature Conservancy, American Rivers) to resource agencies (e.g. U.S. Fish and Wildlife Service, Wisconsin Department of Natural Resources) to infrastructure management agencies (e.g. U.S. Army Corps of Engineers, World Bank). As the science and practice of this topic continues to develop, we anticipate a variety of non-traditional partnerships emerging to address this intersecting conservation and development challenge (Doyle *et al.,* 2008). For instance, 4000 of the U.S.'s 84 000 large dams are 'deficient' (ASCE, 2013) and some publicly owned infrastructure is reaching (or past) its original design life (Juracek, 2014). Simultaneously, ecosystem restoration is a rapidly growing industry (Bernhardt *et al.,* 2005). A growing community of professionals is investigating portfolios of infrastructure that meet infrastructure needs such hydropower and water supply, while also minimizing environmental damage (Ziv *et al.,* 2012), meeting local subsistence fishing and agricultural needs (Richter *et al.,* 2010), and addressing recreational safety (e.g. Kern *et al.,* 2015).

Barrier prioritization provides a unique opportunity to: (i) restore and reconnect potentially large habitat patches quickly and effectively relative to reach-based restoration and (ii) avoid impacts prior to occurrence in line with the mitigation hierarchy (i.e. avoid then minimize then mitigate). This paper synthesizes barrier prioritization studies to date and presents a set of procedures, methods, data sources, and tools for conducting these analyses. Our hope is that this procedure facilitates watershed-scale planning of barrier improvement and avoidance in order to develop and maintain a sustainable portfolio of global water infrastructure.

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