Using structured decision making to overcome scale mismatch challenges in barrier removal for watershed restoration

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Introduction

The removal of barriers, such as dams and culverts, has become a commonly-used approach in river restoration to re-establish the connectivity of river flow, sediment, and species movement (Foley et al. 2017a). These removals have resulted in increases in native species richness, diversity, and productivity (Foley et al. 2017a). Barrier removal is also used to restore commercially important or threatened migratory fish, such as salmonids (family Salmonidae), alosines (family Clupeidae), sturgeons (family Acipenseridae), Sea Lamprey *Petromyzon marinus*, and freshwater eels *Anguilla* spp., by improving the connectivity between feeding and spawning habitats (Pess et al. 2014). While more than 1,400 dams have been removed across America, Asia, Europe, and Australia (Duda et al. 2018), the decision to remove a barrier is usually influenced by objectives beyond restoring local ecosystems or fish populations (Fox et al. 2016). For example, regardless of ecological effects, many old dams in New England are preserved because of their historic value (Fox et al. 2016). Potential effects of barrier removals can occur at a variety of scales, which means the consequences may be felt by diverse stakeholders, making decisions about removal all the more challenging (examples in the following section and Table 1). Here, we examine these challenges, propose the framework of structured decision making (SDM) for addressing them, and test the potential of an applied SDM framework with decision makers and stakeholders in workshops.

Challenges to Decision Making for Barrier Removals

One of the major challenges in decisions about barrier removal and natural resource management is accounting for differences between the scale of planned actions and that of the affected socio-ecological systems, which may limit the effectiveness of the removal project (scale mismatch: Guerrero et al. 2013). Three types of scale mismatch are identified in previous study: spatial, temporal, and functional mismatch (Guerrero et al. 2013). Here we address these scale mismatches in the context of barrier removal.

Failure to consider the ecological and social effects of barrier removal beyond local scales can lead to spatial scale mismatch. The decision to remove or retain a local barrier can lead to changes within and among watersheds by affecting water flows, sediments, pollutants, and nutrients, as well as the movement of species (Foley et al. 2017a; Jensen and Jones 2017; Lin and Robinson 2019). For example, increased freshwater flows and sedimentation resulted in changes in invertebrate and fish community composition in coastal waters after two dams were removed on the Elwha River, Washington (Foley et al. 2017b). Additionally, removal of barriers in one watershed could lead to undesired changes in fish abundance in multiple watersheds, such as the increase of invasive Sea Lamprey in the Great Lakes (Jensen and Jones 2017) or the reduction of fish populations in other watersheds through connections among local populations (Lin and Robinson 2019). Spatial mismatch may also happen when the decision does not reflect the entire socio-ecological system in which it lies (Guerrero et al. 2013). For example, while removing a certain dam might seem logical at a broad scale because funds are available, the owner is willing, and restoration goals would be achieved, opposition from local stakeholders could delay or even prohibit the removal (Fox et al. 2016).

In the case of temporal mismatch, decisions to remove or remediate a barrier are often made without pre-removal assessments, discussions with stakeholders, or a plan for post-removal monitoring (McKay et al. 2016; Foley et al. 2017a) because of limited time horizons for agencies and funding bodies to make decisions. River restoration is a dynamic process, in which the ecosystem undergoes transitional stages before reaching a post-removal stable status (Foley et al. 2017a; 2017b, Fig. 1). Species abundance may decrease rapidly after barrier removal, then gradually recover to a pre-dam or other long-term stable level. However, necessary long-term monitoring to document the functionality of that new stable state rarely occurs (Foley et al. 2017a). Furthermore, decision makers and stakeholders may hold contrasting expectations for dam removal outcomes based on the time horizon they view as relevant to their interests. For instance, those supporting the removal of the Mactaquac Dam in New Brunswick, Canada used the long-term recovery of natural riverscape to envision the outcome, but those opposing the project tended to focus on the (relatively short-term) transition period right after the removal (Reilly and Adamowski 2017). Temporal mismatch could also occur when stakeholder input is limited to only parts of the decision process (Guerrero et al. 2013).

A functional mismatch can occur when the scope, objectives, and actions of the project are focused on the interests of funding bodies and related institutional frameworks, without considering the full scope of ecological processes or threats that will affect the system. For example, in addition to barriers, the persistence of a migratory fish population may also be affected by fishing pressure, climate change, invasive species, and habitat degradation, each of which can operate independently of the barrier removal but can have important effects on outcomes. In addition, the abundance or presence/absence of species in a local habitat patch can also be influenced by changes in regional metapopulation dynamics. Restoration projects could be less effective if the disturbances and dynamics on other parts of the process are neglected. Similarly, functional mismatch can occur when the full value set of stakeholders that support and oppose the project is not considered (Reilly and Adamowski 2017).

Coordinated barrier removal projects (i.e., considering multiple removal projects and the up-downstream relationship among barriers) can improve the cost-effectiveness of restoration plans when comprehensive scales are considered (Neeson et al. 2015). Several decision support tools have been developed to help decision makers evaluate the potential ecological and economic effects of removal over a larger geographic extent (McKay et al. 2016; Lin et al. 2019). These tools are interactive, web-based platforms that provide data, optimization methods, analysis, and visualization functions to support evidence-based decision making. Nevertheless, social and political factors such as social norms, history, identity among local stakeholders, and aesthetic values can heavily influence decisions about barrier removals, but are rarely incorporated into decision support tools (McKay et al. 2016; Lin et al. 2019). These scale mismatches derived from the complex socio-ecological system within which barriers (e.g., dams) exist could reduce the coordination of removals and thus lead to a failure to achieve restoration goals (Fox et al. 2016). To mitigate the negative influence from scale mismatch, using decision support tools and incorporating decision makers and stakeholders from across the geographic and socio-ecological extent that will be affected by the decision into the decision-making process are critical (Guerrero et al. 2013).

Using structured decision making for barrier removals

A structured decision making framework provides a methodical and transparent way to integrate values and objectives from multiple decision makers and stakeholders into the decision making process (Hammond et al. 1999; Fig. 2). While we focused on decisions relevant to barrier removal, the SDM framework could be applied to other restoration projects and natural resources management problems (Conroy and Peterson 2013). Steps in the SDM framework include problem framing, determining objectives, identifying alternatives, estimating consequences, evaluating trade-offs, and deciding and taking actions (Hammond et al. 1999). The involvement of stakeholders from the start of a decision process (problem framing and determining objectives, Fig. 2) can ensure appropriate scales are considered during the development of management plans and build trust between stakeholders and decision makers, which is crucial for the success of environmental management (Irwin et al. 2011; Fox et al. 2016). The effect of uncertainties on decisions could be considered in the process and the feedback arrow (Fig. 2) between the last (deciding and taking actions) and first step (problem framing) provides opportunities for learning and adaptive management. Furthermore, existing decision support tools like Fishwerks (https://greatlakesconnectivity.org/) and FishVis (https://ccviewer.wim.usgs.gov/FishVis/#) and protocols for barrier removal prioritization (McKay et al. 2016; Lin et al. 2019) can be easily integrated into the SDM framework (Fig. 2).

A major task in the early steps of SDM is to frame the problem appropriately, which involves determining the appropriate scales for analysis (Fig. 2). The scale of barrier removal projects varies with the landscape, ecological and policy context, the characteristics of the barrier of concern, and the interests of stakeholders (Table 1). Although using decision support tools and collaborating with environmental scientists can reveal potential scale mismatches in the biophysical regime (Lin et al. 2019), involving social scientists and relevant stakeholders can prevent other mismatches in the socio-ecological system (Robinson et al. 2019). The number and range of relevant stakeholders may vary among projects depending on the potential of the barrier removal to affect the stakeholder and the ability of the stakeholder to influence the removal decision. For example, while the members in local communities are the main stakeholders for removing small dams (Fox et al. 2016), stakeholders for removing a large power-generating dam might include residents in both upstream and downstream areas and resource users beyond the local watershed (e.g., water, electricity, recreational activities, and fisheries; Reilly and Adamowski 2017). Stakeholder analysis matrices and social-network analyses can be used to identify key stakeholders according to the scale of the project (Conroy and Peterson 2013; Guerrero et al. 2013). Here, we suggest ways to address spatial, temporal, and functional mismatches through an SDM framework after identifying key stakeholders.

Spatial mismatches can be addressed by having stakeholders and decision makers explicitly define the geographic and socio-ecological scales relevant to the decision during the problem framing and objectives setting steps of SDM. By defining the appropriate spatial scales early in the decision process, appropriate decision support tools like Fishwerks and FishVis (for more tools, see Lin et al. 2019) with large-scale data can then be chosen to estimate potential consequences and evaluate trade-offs beyond the local scale.

Temporal mismatches resulting from implicitly-defined objectives and measures can be accounted for by using the SDM framework to make these objectives and measures explicit and predict the consequences of removal through participatory modeling with stakeholders (Robinson and Fuller 2017). Decision makers should confirm that objectives, consequences, and post-removal monitoring efforts consider temporal dynamics. Models that simulate the temporal responses of an ecosystem after barrier removal can be used to predict both short and long-term outcomes (Foley et al. 2017a). Anticipated timeframes for the decision-making process, project construction, and monitoring activities can be discussed as a group. In addition, ensuring that all relevant stakeholders are represented, and that the decision team includes environmental and social scientists at the beginning of the process can also minimize temporal mismatch (Robinson et al. 2019).

To reduce possible functional mismatches, decision makers should include environmental and social scientists to identify key ecological and social processes influenced by removal projects, both within the management area and at broader spatial and socio-ecological scales (e.g., multiple watersheds). Then, decision makers and stakeholders can develop objectives, actions, and monitoring activities that incorporate processes and threats at multiple functional scales. After these processes are identified, participatory modelling tools, such as influence diagrams, decision trees, Bayesian belief networks, empirical models, and expert elicitation can be used to reveal the interactions and linkages within and among different processes (Robinson and Fuller 2017).

To facilitate the use of SDM for barrier removal projects, we hosted three workshops in the Great Lakes region, USA and Canada, during 2016-2018. Participants represented state and province-based fish and wildlife agencies (Michigan and Ohio Departments of Natural Resources, Ontario Ministry of Natural Resources and Forestry), federal agencies (U.S. Fish and Wildlife Service, Fisheries and Oceans Canada, U.S. Geological Survey), universities, tribes, non-governmental organizations, and the Great Lakes Fishery Commission. The SDM framework was introduced to all participants through participation in a rapid prototype SDM process for barrier removal case studies, coupled with presentations about relevant issues such as predicting fish production after barrier removal and applying decision support tools for barrier prioritizations. During the workshops, stakeholders' values, which are rarely incorporated in the metrics for barrier removal projects (Fox et al. 2016; McKay et al. 2016), and the interaction among objectives across geographic and socio-ecological scales were identified (Fig. 3). For example, the problem statement identified by participants in the Ohio workshop was "Prioritize barriers throughout the state of Ohio for removal or remediation to maximize native species protection, resources users' satisfaction, and public safety, while minimizing economic costs and complying with existing mandates and regulations" (Fig. 3). The workshops provided participants with an opportunity to learn about SDM and how it can be incorporated into barrier removal decisions at multiple scales in the Great Lakes Basin. These workshops also provided participants with opportunities to communicate with each other and identify potential stakeholders and collaborators beyond the scale in which they primarily work. Through our interactions with these decision makers and stakeholders, we were able to observe a broad consensus that SDM would provide an effective framework for considering the multiple, scale-dependent objectives inherent in barrier removal decisions. We further acknowledge the implementation of SDM process could be time-consuming, therefore applying SDM to projects with many or conflicting objectives could be more cost-effective than using it for projects with a few straightforward objectives or minimal conflicts among stakeholders.

Conclusion

While barrier removal has been widely used to restore riverine ecosystems and migratory fish species by improving connectivity, scale mismatches can cause decision-making to be difficult and sometimes controversial. The use of an SDM framework can help decision makers address scale mismatches by integrating values and objectives from multiple stakeholders and experts across different spatial, temporal, and functional scales in a structured way. Training, including targeted workshops, can help build decision makers' capacity for applying SDM to proposed barrier removals.

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Table 1. Examples of how scale is relevant to barrier removal decisions

Spatial scales and examples	Extent		
	Local reach	**Single watershed**	**Beyond single watershed**
Aquatic species	Resident fish with limited dispersal ability	Migratory fish with a strong homing behavior or a short migration distance	Migratory fish with a weak or no homing behavior or a long migration distance
Sediment, nutrient, and contaminant transportation	Local water quality and turbidity	Downstream water quality and turbidity, downstream and upstream river morphology	River mouth morphology, coastal water quality, turbidity, and primary productivity
Socio-economic factors	Barrier owner(s), property owner(s) around the barrier/impounded area, local community	Property owners and communities in upstream or downstream reaches, resources (water, recreational activities, navigation, fisheries) users within the same watershed	Resources (water, recreational activities, navigation, fisheries) users outside this watershed
Administrative units	Municipality	Multiple municipalities, state/province government	State/province or federal/national government
Temporal scales and examples	**Extent**		
	Short-term (days to weeks)	**Mid-term (months to years)**	**Long-term (years to decades)**

River condition	Sedimentation, upstream erosion, habitat degradation	Habitat access, sediment and flow continuity, riparian vegetation succession, food web development	Approach to pre-dam condition or a new stable state
Socio-economic factors	Construction cost, property and recreational value	Maintenance and monitoring cost, property and recreational value	Maintenance and monitoring cost, recreational and fisheries value
Societal response to landscape change (barrier removal)	Adopted by innovators in the community	Influencing most members in the community	Might become a social norm or be given a historic or cultural value

Functional scales and examples	**Extent**		
	Small	**Medium**	**Large**
Hydrology process/flow regime	Hydrological characteristics in the local reach within one year	Annual variations in the watershed	Inter-annual variations in the drainage basin
Species persistence	Local factors that cause colonization and extinction in habitat patches	Regional factors that influence local metapopulation dynamics	Large-scale (global) factors that affect local species distribution and viability
Ecological processes (other than above two)	Local predator-prey interaction, species movement	Nutrient connection between up- and downstream, or river and floodplain food webs	Material and energy flows between terrestrial-freshwater-marine ecosystems

Social processes	Local demography, economic growth, political and social institutions, cultural value, and knowledge exchange	Regional demography, economic growth, political and social institutions, cultural value, and knowledge exchange	National/international demography, economic growth, political and social institutions, cultural value, and knowledge exchange

Figure captions

Fig. 1. The temporal dynamic of a riverscape before (a), during (b and c), and after (d) barrier removal. Photos were taken by the authors in 2017 for three dam removal projects along the Boardman River, MI, USA, in which (a) is the impounded area of Sabin Dam (intact in 2017), (b) and (c) are the previous dam structure and impounded area of Boardman Dam during the process of removal (removed in 2017), and (d) is a recently restored section of the Boardman River, 4 years after the removal of the Brown Bridge Dam (removed in 2013).

Fig. 2. The integrated use of SDM framework (dark grey boxes), protocol for barrier removal prioritization (light grey boxes, McKay et al. 2016), and decision support tools (blue shaded area).

Fig. 3. Objective hierarchies for barrier removal prioritization identified at the second step of SDM framework (determining objectives) in a workshop in Bay Village, Ohio, USA, with staff from the Ohio Department of Natural Resources (September 2018). Dark grey boxes represent fundamental objectives, light grey boxes represent means objectives with measurable attributes or methods to assess the attribute in parentheses, and the unshaded box represents a process objective. T&E species represents threatened and endangered species and AIS represents aquatic invasive species. Objectives with different scales (e.g., the local sport fish and the lake-wide invasive Sea Lamprey production; short-term construction costs and long-term maintenance costs, species conservation and resource user’s satisfaction) across the socio-ecological system were unveiled.