Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings

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A key challenge in aquatic restoration efforts is documenting locations where ecological connectivity is disrupted in water bodies that are dammed or crossed by roads (road crossings). To prioritize actions aimed at restoring connectivity, we argue that there is a need for systematic inventories of these potential barriers at regional and national scales. Here, we address this limitation for the North American Great Lakes basin by compiling the best available spatial data on the locations of dams and road crossings. Our spatial database documents 38 times as many road crossings as dams in the Great Lakes basin, and case studies indicate that, on average, only 36% of road crossings in the area are fully passable to fish. It is therefore essential that decision makers account for both road crossings and dams when attempting to restore aquatic ecosystem connectivity. Given that road crossing structures are commonly upgraded as part of road maintenance, many opportunities exist to restore connections within aquatic ecosystems at minimal added cost by ensuring upgrade designs permit water flow and the passage of fish and other organisms. Our findings highlight the necessity for improved dam and road crossing inventories that traverse political boundaries to facilitate the restoration of aquatic ecosystem connectivity from local to global scales.

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Dams (Figure 1a), road crossings (Figure 1b), and other engineered structures act as barriers to ecological processes in aquatic ecosystems worldwide. Consequently, these barriers affect upstream connectivity by blocking animal migrations (Figure 1c; Pépino *et al*. 2012); affect downstream connectivity by retaining nutrients (Figure 1d; Stanley and Doyle 2003), materials (Figure 1d; Andersson *et al*. 2000), and organisms (Figure 1c; Nagrodski *et al*. 2012); and affect lateral connectivity by diminishing flood pulses (Lemly *et al*. 2000). Although dams and roads offer a range of societal benefits, such as water resource management, power generation, and transportation, there is a broad consensus that the costs and benefits of these structures should be re-evaluated to account for their ecological impacts (Lehner *et al*. 2011). Increasingly, society has been willing to assume the costs of improving or removing engineered structures that serve little purpose in exchange for increasing aquatic ecosystem connectivity.

In a nutshell:

- Systematic inventories that document where aquatic ecosystems are dammed or crossed by roads are needed to guide restoration efforts in large basins
- In North America's Great Lakes basin there are 38 times as many road crossings as dams, and roughly two-thirds of road crossings are either partially or completely impassible to fish
- Given the prevalence and relatively low replacement cost of road crossings, these potential barriers offer abundant opportunities to enhance connectivity in large aquatic ecosystems

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Migratory fish species often travel long distances, crossing through multiple watersheds and political boundaries, including counties, states, territories, provinces, or countries, to reach spawning sites. Given the broad ranges of most migratory fish species, there are often several options available for improving access to spawning habitat. Making decisions for a single barrier or watershed without consideration of the broader basin context could therefore be less effective and more costly than efforts that consider the basin as a whole to evaluate the relative efficiency of different management actions (eg Erasmus *et al*. 1999; Kark *et al*. 2009). Basin-scale decision making can maximize the positive effects of barrier remediation with cascading ecological benefits, both upstream and downstream (Kemp and O'Hanley 2010).

There have been few comprehensive assessments aimed

Figure 1. *Restoring connectivity between aquatic ecosystems is a global conservation priority. Connectivity between aquatic ecosystems can be enhanced by remediating barriers such as (a) dams and (b) road crossings. These barriers can (c) prevent fish from reaching high-quality breeding habitat, as well as inhibit the movement of (d) nutrients and other material.*

at restoring connectivity within large aquatic ecosystems. However, a key lesson has been learned from one pioneering effort: The Nature Conservancy's Northeast Aquatic Connectivity Project (Martin and Apse 2011) demonstrated the value of accessible data on the locations of potential barriers. Data on the location and characteristics of engineered structures are sometimes available or can easily be collected locally (Bourne *et al.* 2011), but this is rarely true at broader scales (Panel 1). For instance, although a comprehensive global database of large dams is avaliable (Lehner *et al.* 2011), there are no comparable databases of road crossings or smaller dams. Effective prioritization of barrier remediation efforts rests on mapping the occurrence of engineered structures and collecting information about whether these structures are passable to fish and other species.

In this paper, we show how data availability and completeness can influence barrier remediation decisions in large basins. Using the North American Great Lakes basin (hereafter "Great Lakes") as a case study, we merge several existing spatial databases for dams and then develop a new database of road crossings that are also likely to hinder connectivity between these large lakes and their tributaries. Our assessment spans the entire basin, which we define as the five Great Lakes and their drainage area, exclusive of connecting channels and outlets. Specifically, our objectives are to: (1) summarize existing spatial data on dams for the Great Lakes and present a new georeferenced inventory of road crossings that are potential barriers, and (2) compare the spatial distribution and passability of dams and road crossings throughout the Great Lakes. Our analysis indicates that expanding inventories of potential barriers is essential for prioritizing actions to restore connectivity in aquatic ecosystems.

Inventorying potential barriers in the Great Lakes

The Global Reservoir and Dam (GRanD) database (Lehner *et al.* 2011) is a comprehensive global database of large reservoirs (> 0.1 km^3 storage capacity) and their associated dams. For the Great Lakes, GRanD contains information on dams ranging in height from 2–90 m (Table 1). In the US, the most comprehensive inventory of dams is the National Anthropogenic Barrier Dataset (NABD; Table 1), which is a refined version of the US Army Corps of Engineers' 2009 National Inventory of Dams (NID). The NABD improves on the 2009 NID by georeferencing dams with respect to the US National Hydrology Dataset Plus (NHDPlus; www.horizon-systems.com/nhdplus/). In the Great Lakes, dams in the NABD range from 1–75 m in height. We cross-checked the locations of dams listed in the NABD to ensure they were also accurately linked with the US National Hydrology Dataset (NHD; Table 1), which is mapped at a higher resolution than the NHDPlus. We used the NHD rather than the NHDPlus for our analysis because the former is mapped at a similar scale to the National Hydro Network (NHN; Table 1) in Canada. There is no publicly available Canadian counterpart to the NABD.

To expand on these traditional sources of dam spatial data, we collated additional dam records from the Michigan Institute for Fisheries Research (IFR) and the Ontario Ministry of Natural Resources (OMNR) (Table 1). These dams had not previously been georeferenced to the NHD or NHN, so we applied a three-step process to identify their exact locations. First, we used Google Earth to identify the spatial location of each dam. Second, using ArcGIS 10 and Google Earth, we eliminated duplicate records within the collated database by cross-checking visual identification, dam names, and occurrences within a 50-m buffer of another dam. Finally, using ArcGIS 10, we linked all dam records to the NHD and

NHN stream networks. Any dams that did not occur on the NHD and NHN stream networks were excluded; this affected only dams on very small tributaries or those that were distinct from any identified river network (eg dams associated with mines).

Because there were no existing databases of road crossings in the Great Lakes, we created a new database, encompassing the US and Canada. To identify the location of road crossings, we intersected the stream reaches in the NHD and NHN with highways, county roads, and local roads mapped by the US Census and OMNR (Table 1). These intersection points constitute a minimum estimate of road crossings in the Great Lakes.

Data resolution and the perceived number of potential barriers

We systematically compared the number and distribution of potential barriers that would be accounted for by decision makers using the databases outlined above. The GRanD database lists only 118 very large dams for the Great Lakes (Table 1), 101 of which are within the US. The NABD database offers much better coverage, documenting nearly 15 times as many dams as the GRanD database, but is limited to the US.

In the US, the IFR data add 2140 georeferenced dams to those documented in the NABD (Table 1). Apart from the GRanD database, OMNR is the only source for dam records on the Canadian side of the Great Lakes, and adds 3460 georeferenced dams (Table 1). In total, we estimate that there are at least 7091 dams on the tributaries of the Great Lakes and that they are evenly divided between the US and Canada (Figure 3a).

We estimate that there are also 268 818 road crossings – equivalent to 38 times the number of potential barriers in our compilation of dams in the Great Lakes region, 69% of which occur within the US (Figure 3b). Overall, the combined database includes 275 909 potential barriers – road crossings and dams – within the Great Lakes tributaries; in other words, one potential barrier occurs every 2 river kilometers.

The importance of passability

In addition to knowing the locations of dams and road crossings, decision makers also need information on how passable engineered structures are for species of interest. Understanding the ecological impacts of these structures

Panel 1. Case study – possible consequences of incomplete dam and road crossing inventories

Spatial data on the occurrence of dams and road crossings are critical for broad-scale decision making aimed at restoring aquatic ecosystem connectivity in large basins. If spatial data cannot be easily accessed, are incomplete, or are not provided at a common spatial resolution, then decision makers are unable to evaluate all possible options to restore aquatic ecosystem connectivity, which could lead to over- or underestimations of the value of management actions. Here, we use two management scenarios from our ongoing work in Wisconsin to demonstrate the potential implications of this situation.

In Green Bay, managers seek to maximize access to upstream wetland habitat for native northern pike (*Esox lucius*) that migrate into tributaries to spawn in spring. Initially, the managers planned to build a fish-passage structure around a dam (Figure 2a) on Duck Creek (a small tributary of Lake Michigan) to improve access to wetland spawning habitat for northern pike. During the planning phase of this project, an inventory of road crossings was conducted in the watershed; of the two crossings upstream of the dam (Figure 2a), one was determined to be partially passable and the other impassable for fish. While passage around the dam would provide access to an additional 4 ha of wetland at a cost of US$87 000, reconstruction of the road crossings would cost an additional US$120 000 and would open access to an additional 70 ha of wetland. The project would therefore be approximately 12 times as cost-efficient if road crossings were included. If the additional surveys of road crossings had not been performed, the project would have overestimated the value and benefits gained from the fish-passage structure alone.

In the Pine River watershed of northeastern Wisconsin, managers wish to maximize access to habitat for native stream-resident fish such as brook trout (*Salvelinus fontinalis*), mottled sculpin (*Cottus bairdii*), and several minnow species (eg central mudminnow, *Umbra limi*). The Pine River has a large dam (not under consideration for removal) on its mainstem near the river's confluence with the Menominee River. Initially, it appeared that the 600 km of river upstream of the dam was largely open to movement by stream-resident fishes. However, an inventory of road crossings revealed that 38 of the 66 first-order tributaries in the watershed were isolated from the main river channel by road crossings (Figure 2b). These isolated tributaries had, on average, fewer fish species than did the connected tributaries. Thus, identifying impassable road crossings within the watershed strongly influences the decisions regarding barrier remediation. By restoring connectivity between the Pine River and its first-order tributaries, managers can maximize the total amount of habitat available to native stream-resident fish.

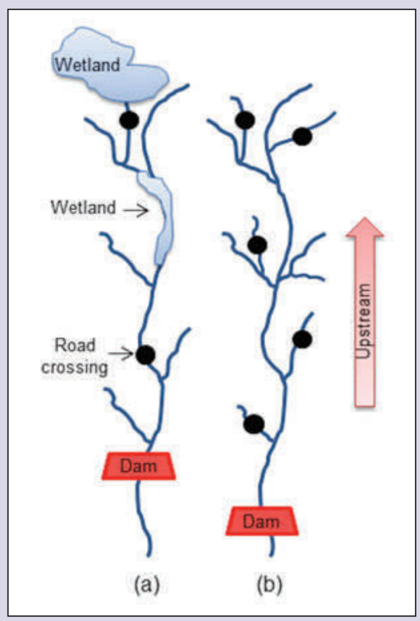

Figure 2. Management scenarios that aim to maximize connectivity between aquatic systems to benefit (a) native migratory fish species, or (b) native stream-resident fish species. In both scenarios, the dams in red were known barriers to fish migration at the start of the decision-making process; the black circles represent road crossings of unknown impact.

Table 1. Spatial data used to map the occurrence of potential barriers in the North American Great Lakes basin

Potential barrier type	*Spatial databases*	*Sources*	*Number of potential barriers*
Dams	Global Reservoir and Dam (GRanD) database	Lehner *et al.* (2011)	118
	National Anthropogenic Barrier Dataset (NABD)	www.ecosystems.usgs.gov/fishhabitat/	1491
	Michigan Institute of Fisheries Research (IFR)	www.snre.umich.edu/coe/Fisheries	2140
	Ontario Ministry of Natural Resources (OMNR)	www.mnr.gov.on.ca/en/	3460
Road crossings	US National Hydrography Dataset (NHD; 1:24 000)	www.nhd.usgs.gov/	
	US Census Tiger Roads	www.census.gov/geo/www/tiger/shp.html	
	Canadian National Hydro Network (NHN; 1:20 000)	www.geobase.ca/geobase/en/index.html	
	Ontario's Road Network, OMNR	www.mnr.gov.on.ca/en/	268 818

on aquatic connectivity is essential when prioritizing efforts to maximize returns on limited funding.

It is challenging to quantify how passable engineered structures are to fish and other organisms due to variability in structure shape and size, and because tributary water levels vary seasonally and annually. Subsequently, there are many common definitions of structure "passability", which are quantified by various methods. Quantifying the passability of fish-passage structures installed at dams is unique to each structure as they are often designed with particular species in mind, but may function poorly for non-target species. Despite the large body of literature concerning the success of fish-passage structures, insufficient monitoring methods complicate drawing substantial conclusions about the success of each one in facilitating even targeted fish species' movements around dams (Roscoe and Hinch 2010). Similarly, identifying large or very large dams that act as complete physical barriers to fish is relatively straightforward when the physical dimensions of the structure are known. However, there is often limited information about the dimensions of smaller low-head dams, more commonly known as weirs, making it difficult to quantify how passable they are to fish (eg Porto *et al.* 1999). Attempts at quantifying road crossing passability are more numerous than for dams (eg Poplar-Jeffers *et al.* 2009; Pépino *et al.* 2012), and have been reviewed recently by Kemp and O'Hanley (2010). Bridges are generally considered to be completely passable by all fish species, whereas culverts vary in terms of passability, depending on factors such as diameter, length, slope, outlet configuration, and other characteristics that influence a fish's ability to migrate through (Kemp and O'Hanley 2010).

Given that road crossings are abundant in all developed nations, it is critical to account for these structures when prioritizing aquatic ecosystem restoration efforts. Our analysis shows that the challenge of restoring aquatic ecosystem connectivity in the Great Lakes will be greatly underestimated if road crossings are not assessed, but likely overestimated if all road crossings are assumed to be impassable. The need for passability information is illustrated by comparing detailed field assessments of all road crossings (n = 1403) in four case studies in different parts of the Lake Michigan and Lake Superior basins (Figure 4). In these four areas, attributes of the road crossing structure, based on the protocol from the Great Lakes Aquatic Connectivity Project (www.conserveonline.org/workspaces/streamconnect/) and a set of expert guidelines, were used to determine if a structure was passable, partially passable, or impassable for a range of native fish species, including both small-bodied fish such as creek chub (*Semotilus atromaculatus*) and larger-bodied fish like northern pike (*Esox lucius*). A structure was considered passable if the expert-defined thresholds indicated that all native fish species could pass through during most stream flows; a structure was considered partially passable if some species or life stages could not move through the structure during most stream flows; and finally, a structure was deemed impassable if most species and life stages could not get through at most stream flows. Even con-

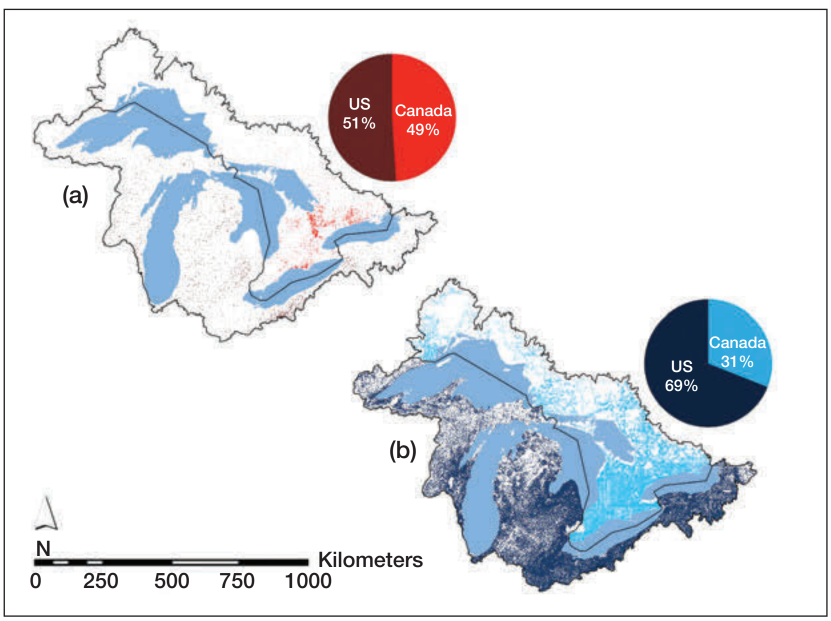

Figure 3. *Location of potential barriers in the North American Great Lakes basin: (a) dams and (b) road crossings.*

sidering the "worst-case scenario" presented by the Pike River watershed (one of the four case studies; O'Hanley 2011), where only 1% of structures were fully passable, at least 41% of structures were partially passable and could have been targeted for improvements to enhance connectivity. Results from the other three case studies suggest higher passability levels (Figure 4). Applying the average percentage of impassable (35%) and partially passable (29%) road crossings from these four case studies to the entire Great Lakes suggests that roughly 172 000 road crossings (24 times the total number of dams) might be impassable or partially passable for some species. The variability of the findings in these four case studies (Figure 4) underscores the need for on-the-ground surveys. Data from such surveys could inform models that predict passability of unsampled structures across large areas like the Great Lakes.

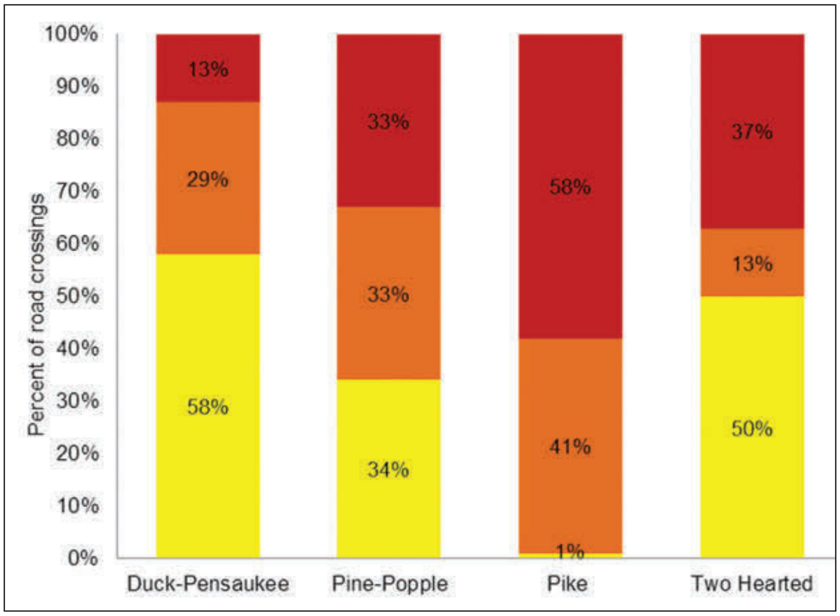

Figure 4. *Percentages of road crossings that are passable (yellow), partially passable (orange), and impassable (red) in the four case study areas: Duck-Pensaukee, Pine-Popple, and Pike study areas in the Lake Michigan basin, and the Two Hearted study area in the Lake Superior basin.*

Road crossings versus dams

The numerical dominance of road crossings over dams as potential barriers in the Great Lakes is likely to apply to most other regions of the world as well. Road crossings are more prevalent in landscapes where human transportation networks have been developed. From the management and policy perspectives, this disparity represents a greater number of opportunities to improve road crossings than to improve or remove dams. Enhancing passability of road crossings is also likely to be more economically feasible than removing dams or installing fish-passage structures, and could be more socially acceptable given that dams often provide multiple public benefits (eg Johnson and Graber 2002). As argued by Doyle *et al.* (2008), the National Infrastructure Improvement Act of 2007 offers opportunities to restore aquatic ecosystem connectivity by promoting the improvement of degraded road infrastructure in the US. For example, exchange of information between conservation and infrastructure managers can enable road crossings to be improved in environmentally beneficial ways during routine road maintenance (eg Valentine-Rose and Layman 2011). This common-sense strategy maximizes ecological benefits and can often minimize additional costs to all parties (eg Giles *et al.* 2010).

As dams approach the end of their projected lifetime, regulatory processes and basic maintenance may create similar opportunities for dam upgrades to enhance passability (Doyle *et al.* 2008). However, the high costs associated with altering or removing dams will continue to be prohibitive, particularly in large or steep watersheds. Although costs are rarely reported publicly, analyses by Roni *et al.* (2005) and Bernhardt *et al.* (2005) illustrate the differential costs associated with road-crossing improvements and dam removals across the US. From 1990 to 2003, road-crossing improvements (n = 420) averaged US$137 000, whereas dam removals (n = 799) averaged US$1.1 million. More recent estimates for the Pike River watershed in the Great Lakes were US$2000 for road-crossing repairs and US$500 000 to remove a medium-sized dam (O'Hanley 2011). While the costs of modifying or removing infrastructure will vary across regions and countries, the average cost of removing a dam is generally higher than that of improving a road crossing. In addition, road crossings have a shorter replacement cycle than dams, thereby offering more frequent opportunities for fish-friendly improvements to be made. The historical emphasis on dams as barriers to connectivity in the Great Lakes should be expanded to include assessments of road crossings, which could offer effective and economically feasible targets for restoration.

Balancing ecological, socioeconomic, and political considerations in spatial prioritization

Prioritizing remediation efforts across the immense number of potential barriers identified in our analysis is daunting. The costs and benefits of remediation actions can vary tremendously, depending on the condition of the structure in question and on regional socioeconomic factors (Wilson *et al.* 2011), further complicating prioritization strategies to maximize the ecological and socioeconomic benefits while minimizing costs (O'Hanley 2011). Nonetheless, spatial prioritization methods – analyses of available information aimed at addressing a particular environmental planning problem (Moilanen *et al.* 2009) – are commonly applied at regional scales that allow alignment of priorities across political boundaries, at scales that are meaningful to species and ecosystem processes. By accounting for connectivity between areas and the contribution of each action or set of actions toward achieving an explicit objective, quantitative prioritization methods identify actions that yield the maximum benefit (or minimum cost) given one or more operational or resource constraints (Januchowski-Hartley *et al.* 2011; O'Hanley 2011). Indeed, spatial prioritization methods offer more efficient solutions than commonly used scoring or ranking methods to prioritize barrier improvement and removal actions (O'Hanley and Tomberlin 2005). The spatial database of dams and road crossings presented here makes such analyses possible for the first time in the Great Lakes.

Identifying priority actions to restore aquatic connectivity also requires an understanding of ecological, socioeconomic, and political constraints (and access to relevant data) that could influence the effectiveness of implemented actions. Factors that should be considered include: (1) the existing condition of aquatic systems (Blais *et al.* 2007), (2) the current and historical distribution of important habitat (Hall *et al.* 2010), (3) the costs of implementing actions (eg O'Hanley 2011), (4) the opportunities available at sites where individual barriers no longer provide services (Doyle *et al.* 2008), (5) the social factors that influence stakeholders' attitudes toward the removal or retention of barriers (Johnson and Graber 2002), and (6) how decisions made in one geopolitical area could influence decisions made in another (eg Kark *et al.* 2009). In the Great Lakes, for instance, decision makers are currently faced with many competing costs and benefits; retaining barriers help to control nonnative species but also negatively impact native fish species richness (Harford and McLaughlin 2007). Weighing these factors against the ecological benefits gained from restoring connectivity is a reality that decision makers must face as the removal of aging infrastructure becomes necessary (eg Stanley and Doyle 2003). With these examples in mind, there is a clear need for the development and application of methods that can produce practical and cost-effective solutions.

Conclusions

Recognition of the detrimental impacts of dams and road crossings on valued aquatic species and ecosystem services in the Great Lakes has led to enormous planning and funding efforts. For example, the Great Lakes Restoration Initiative (GLRI; www.glri.us) has already allocated roughly US$1 billion of a requested US$5 billion toward restoring ecosystem health, including reestablishing connectivity between the Great Lakes and their tributaries. Despite the acute need, resource management agencies in the Great Lakes currently lack a systematic framework for choosing actions that will maximize connectivity at the basin scale while incurring the lowest possible costs. The inventory of potential barriers presented in this paper is a first step toward facilitating informed and cost-effective decision making for GLRI and other initiatives at the basin scale. However, maintaining the accuracy and robustness of this database will require continued input of new data from government agencies and non-governmental organizations. In particular, new data on structure passability from on-the-ground surveys are essential, and the database must be updated as barriers are removed or altered. Including data on the structural condition of dams and road crossings as well as restoration costs would also be helpful.

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