Pet project or best project? Online decision support tools for prioritizing barrier removals in the Great Lakes and beyond

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ABSTRACT

Structures built through river networks serve a variety of societal needs including transportation, hydroelectric power, and limiting species invasions; however, these barriers sharply reduce breeding habitat available to migratory fishes. The benefits to fish of removing any particular barrier depends on its location within the river network, its passability to fish, and the relative position of other barriers. To facilitate barrier removal prioritization within the Great Lakes basin, we developed an online decision support tool with three functions: visualize existing barriers; correct barrier attributes; and run optimization models to identify portfolios of removals that would provide access to the greatest amount of stream channel for a specified budget. A survey of similar tools addressing aquatic connectivity indicates barrier visualization is becoming widespread but few allow scenario analysis or optimization. Having these additional functions, our DST enables practitioners, funders, and managers to develop priorities based on cost-effectiveness in restoring aquatic connectivity.

INTRODUCTION

Roughly 2,400 tributary rivers enter the Laurentian Great Lakes, creating one of the largest freshwater ecosystems in the world. These lakes and their watersheds provide recreation, jobs, and ecosystem services to 95 million people (Vaccaro and Read 2011; Allan et al. 2015; Campbell et al. 2015). In the services sector of the economy, which includes tourism, sport fishing, and boating, the net value of the lakes is estimated at $2.7 trillion annually (Campbell et al. 2015). As the region has prospered, people have constructed dams in nearly every watershed, and culverts for road crossings are many times more abundant than dams. This infrastructure has fragmented fish habitat in Great Lakes tributaries (Januchowski-Hartley et al. 2013; Neeson et al. 2015) affecting dozens of fish species. However, dams and road culverts also serve critical societal needs for power generation, flood control, transportation, and control of invasive species (e.g. Lavis et al. 2003; Stokstad 2010; Clarkson 2004; Novinger and Rahel 2003). This diversity of costs and benefits complicates decisions about restoring tributary connectivity for migratory fishes. Moreover, barrier management involves numerous governing bodies and interest groups whose priorities must be reconciled with regard to barrier removal or placement decisions.

Due to the dendritic nature of river networks, fragmentation is particularly problematic for migratory fishes; a single impassable barrier can prevent access to habitat in many different branches of the network (Dodd et al. 2003; McLaughlin et al. 2006). Over 270,000 potential barriers exist on Great Lakes tributaries (Januchowski-Hartley et al. 2013), which collectively prevent fish from reaching 64% of tributary channel length and partially block an additional 23% (Neeson et al. 2015). Within this inventory of barriers, we estimate that over 100,000 are on channels large enough to affect spawning habitat access for migratory fishes including important sportfish such as salmon, brook trout, walleye, and northern pike (McLaughlin et al. 2006). Numerous species of non-game, native fishes like sturgeon and suckers are also strongly affected, as well as certain prey species like darters and shiners (McLaughlin et al. 2006). These upstream fish migrations support recreational and commercial fisheries, and also provide a significant source of nutrients for tributary ecosystems (Flecker et al. 2010) that boost the productivity of stream food webs (Schuldt and Hershey 1995; Levi and Tank 2013; Childress and McIntyre 2015).

There is growing interest in removing barriers to restore Great Lakes tributary connectivity but conservation practitioners face a daunting task in choosing among candidate projects. Decision support tools (DSTs) can merge visualization and analytical capabilities in order to provide a powerful and flexible means of evaluating the consequences of various connectivity restoration scenarios. Spatially-explicit DSTs can range from maps of habitat use by species (Wall et al. 2004; Sowa et al. 2007) to interactive tools to plan conservation areas (Segan et al. 2011), wind farms (Simão et al. 2009), or evaluate potential targets for restoration (Rao et al. 2007). Well-designed DSTs can provide transparency in evaluating alternative decisions as part of a structured decision making process (Gregory and Keeney 2002). Given the growing interest in barrier removals from Great Lakes tributaries, there is a need for a spatially-explicit DST to enable visualization of tributary connectivity and to enable strategic analysis of alternative removal scenarios.

The challenges within the Great Lakes region, as in many other settings, are three-fold. First, the lack of a centralized barrier database hampers spatial planning efforts particularly at large scales. Second, spatial contingencies among projects make it all but impossible to evaluate the costs and benefits of any one barrier removal project in isolation, necessitating the use of sophisticated computational approaches such as graph theory or optimization. Third, choosing among candidate projects necessarily involves navigating complex trade-offs between ecological and societal values that are incommensurable. For example, the potential ecological effects of barrier removals could have both positive (via native species) and negative (via invaders and pathogens) consequences (McLaughlin et al. 2013), not to mention implications for human safety and recreation. Optimization models are ideally suited for dealing with these sorts of challenges. By explicitly accounting for interdependencies among decisions (e.g., the cumulative effect of multiple barrier removals on connectivity), they account for the benefits of coordinated actions to ensure the most efficient allocation of resources for restoration. Moreover, when applied to settings in which multiple objectives must be balanced, accessible optimization models enable decision makers to explore the consequences of alternative actions to clarify potential tradeoffs.

Great Lakes Connectivity DST Development

We created a web-based decision support tool called FishWerks (greatlakesconnectivity.org) that allows users to: (1) visualize all mapped barriers within the Great Lakes Basin; (2) update the database when new data about existing barriers becomes available; and (3) run optimization models to identify potential sets of removals that maximize tributary access for Great Lakes migratory fishes within a specified budget.

<u>The science behind the tool</u>

The map of tributary streams used in the DST was created specifically for aquatic connectivity analyses (Diebel et al. In prep) and updates previous hydrography (Januchowski-Hartley et al. 2013, 2014; Neeson et al. 2015). The DST hydrography is a subset of the 1:100,000-scale flowlines of the National Hydrography Database Plus Version 2 (NHD Plus V2 2012) and Ontario Integrated Hydrology Dataset (OMNR 2013), pruned to the extent of the Great Lakes Aquatic Habitat Framework's synthetic drainage lines (Wang et al. 2015; Forsyth et al. In review). This hydrography dataset includes 2,404 tributaries, ranging from small coastal streams draining as little as 2.7 km^2, to large rivers with thousands of km of total tributary length. The barrier layer currently includes 99,940 road crossings and 3,954 dams (Figure 1) but the exact number changes through user-contributed edits (details below). The barrier map improves on the previous version of our barrier database (Januchowski-Hartley et al. 2013, 2014; Neeson et al. 2015) because it is referenced to the updated DST hydrography and underwent additional barrier feature verification using aerial images. We do not currently account for natural barriers (e.g., waterfalls and chutes), but will add these features as soon as spatially complete data on their locations is assembled.

To optimize barrier removal decisions, we formulated a mathematical model that compares all possible sets of barriers to identify the portfolio of removals that would provide the greatest increase in tributary channel length available to migratory fishes. The model allows users to first specify the geographic area of interest and available budget. Stream length gains for a particular removal are calculated as the stream length of all upstream reaches multiplied by the increase in cumulative passability of the barrier. The benefits of a given barrier removal is down-weighted if up-stream barriers are not also removed. Cumulative passability is estimated as the product of the passability rating of a particular barrier and all downstream barriers. To find the optimal portfolio of barrier removals, our model employs a general purpose mixed integer linear programming approach (Wolsey 1998; Conforti et al. 2014).

Our barrier prioritization methodology is underpinned by two additional data types that have been previously published: the passability of road crossings (Januchowski-Hartley et al. 2014), and the costs of dam removal or road crossing replacement to ensure full passage of migratory fishes (Neeson et al. 2015). Barrier passability is defined as the estimated proportion of fish able to pass through or over a barrier while migrating upstream (Kemp and O'Hanley 2010). It can also be thought of as the probability that a given fish can successfully pass a particular barrier. Following Januchowski-Hartley et al. (2014), we used stream characteristics to model water velocity and outlet drops at road crossings. These modeled variables were translated into passabilities for three classes of fish with different swimming abilities (Table 1). The water velocity thresholds for these swimming classes were 0.4 m/s (weak swimmers), 0.7 m/s (moderate swimmers), and 1.0 m/s (strong swimmers). Each species was assigned to a class based on swimming speeds reported in the literature when possible or based on expert opinion when necessary. We calculated the cost of removing dams based on an analysis of completed dam removals in the Great Lakes basin (see Neeson et al. 20015 for a discussion of model fit and data limitation), while the cost of replacing a culvert was estimated from stream size, material, labor costs, and road characteristics (Neeson et al. 2015).Our model focuses on barrier removal rather than alternative means of restoring passability (e.g., installing fish ladders or elevators) because of the complexity of estimating initial and recurring costs for these mitigation options.

DST Structure and Features

FishWerks has been developed as a web-based application where the primary logic and processing are hosted on a centralized server and accessible via a web browser. The application is currently hosted at the Wisconsin Institute for Discovery at the University of Wisconsin, Madison and runs in most modern web browsers without any additional requirements. The barrier viewer (Figure 2) has an interactive base-map, which allows users to zoom in at any scale from the entire basin (1:35,000,000 scale) down to local neighborhoods (1:15,000 scale). The base maps are supplied by Google maps, and roads, cities, rivers, and other features are labeled automatically against hybrid or satellite views. Barriers are shown as colored squares and clicking on them brings up a data viewer at the bottom of the screen, which lists the type of barrier (dam or road crossing), associated drainage lake, passability for various fish groups, latitude/longitude, and a unique barrier identification number. A set of filters in the sidebar enables users to easily select barriers with certain characteristics (e.g., all road crossings with a removal cost less than $100,000 in Michigan). There are jurisdictional filters (nation, state/province, county) and hydrographic filters (watershed, lake basin) that can be toggled on or off, as well as barrier-level filters from our database, including barrier type, removal cost, passability, and upstream channel length. When a subset of barriers is selected, the markers are highlighted to facilitate visualization.

Virtually any large-scale mapping effort is sure to include database errors that would be obvious to local experts. Such short-comings can be addressed by enabling users to identify and correct errors as a core function of the DST itself. On our website, such crowd-sourcing is implemented by selecting the “Wild West” database option, then editing the barrier attribute data seen in the viewer. The modified database can be edited only by registered users and saved changes are integrated into analyses run within the Wild West database. Administrators of the DST website review the Wild West database periodically and transfer approved modifications to the primary database for general use. The greatest revision of this database is likely to be as FishWerks rolls out and local experts correct our barrier inventory which has been assembled from diverse sources that vary in time period and attribute availability. For this reason, we plan to verify changes quickly during the initial year of the project and thereafter on a semiannual basis. This crowd-sourcing process allows the DST to be refined constantly by qualified users.

A unique aspect of FishWerks is that it allows users to develop custom scenarios of barrier removals to explore which combination of removals would make the most stream length accessible for a given budget. There are three ways in which barriers can be designated prior to launching an analysis: ‘ignore,’ ‘remove,’ or ‘optimize.’ The ‘ignore’ designation allows users to exclude certain barriers from consideration for removal. For instance, one might wish to ignore dams built for hydroelectric power or sea lamprey control since they are unlikely to be removed. The ‘remove’ setting forces the inclusion of barriers into the final list of proposed removals. This setting could be employed if users wanted to designate a dam or road culvert for removal because of safety concerns (i.e., the barrier is in a state of disrepair) or because funding available from other sources makes removal a certainty. The ‘optimize' designation includes all remaining barriers to be considered for removal (i.e., not in the ‘ignore’ or ‘remove’ categories) by the optimization model. In the optimization settings, users are prompted to specify the total available budget prior to analysis. Given a small number of barriers or a small budget, the optimization model runs within a few seconds. For example, to solve for all barriers around Lake Ontario (n = ~17,000) and a $10 million budget, the optimization run completes in about 20 seconds. As the list of potential barriers expands and the budget is comparatively small, the computational complexity and time required to solve the problem can increase. Running an optimization with all barriers in the Great Lakes Basin and a $10 million budget takes over a minute to solve, while the same barrier set with a $1 million budget, takes over 15 minutes to calculate the recommended set of barriers. For this reason, we have included a ‘fast-solve’ option, which can provide an answer quickly using a heuristic solution method that relaxes the level of confidence that the suggested set of removals is truly the optimal solution. In the case of longer runs, registered users have the option of being notified by email when the optimization is complete.

After an optimization analysis is complete, the map displays the location of all barriers included in the optimal portfolio of barrier removals and graphical summaries of the results appear. The graphs display the cumulative stream length expected to be gained from the optimal portfolio of barrier removals including tributary channel made accessible (absolute length or percent change), and the associated return on investment (channel length per dollar). The map of barriers suggested for removal is displayed onscreen, and a list of barriers and their associated attributes can be exported as a CSV file. To facilitate comparisons among alternative budgets or sets of ignored/removed barriers, registered users can also save model results to create graphs comparing multiple analyses.

Example applications

Maximizing restoration efficiency at large spatial scales. The return on investment from barrier removals generally increases with the size of the area analyzed because more options can be considered simultaneously, thus boosting the likelihood of identifying high-return, low-cost removals, as well as synergistic removals within the same watershed. For instance, with a generous budget of $100 million, optimizing removals over the entire Great Lakes Basin suggests the potential to double the length of stream accessible to migratory fishes, whereas separate optimizations for each tributary yields only a 14% increase in fish habitat (Neeson et al. 2015). Even at a state-level, our optimization analysis tool can rapidly suggest a coordinated portfolio of projects that increases potential fish habitat far more than selecting projects based on their individual merits.

Making the most of a small budget at small spatial scales. For organizations with modest means and a well-defined region of interest, FishWerks can rapidly identify which of the affordable barrier removals would yield the greatest stream length gains. For instance, a county road manager could select their jurisdiction, enter a budget cap, and see which road crossings are expected to be most problematic for migratory fishes within seconds. If the county has already planned to replace one or more crossings, including these in the optimization can enable the DST to suggest which additional projects would best foster synergies.

Identifying opportunities for collaboration across organizational boundaries. When FishWerks is asked to evaluate all barriers within a limited region using a large budget, users can see which barriers would open the most potential habitat for fish. Removal of these barriers might be beyond the budget of any one organization but could serve as an overarching target for collaborative efforts or fundraising goals. Additionally, FishWerks can promote coordination between multiple jurisdictions in the same tributary system by identifying opportunities for cooperation through synergistic barrier removals. For example, a county-level plan might benefit from accounting for actions proposed by a neighboring county, or state and federal agencies.

Because the cumulative passabilities of barriers in a stream network are inter-dependent, the return on investment achieved by all parties may be boosted by planning complimentary efforts across jurisdictions.

CONCLUSION

FishWerks, our DST for prioritizing barrier removals in the Great Lakes, is one of many restoration DST websites focused on aquatic connectivity in North America (Table 2). A large majority of these tools focus purely on barrier visualization which is an essential first step in any prioritization. A few of these tools also display the length of unobstructed river length upstream of dams, but very few address road crossings as a form of barrier. Our DST appears to be unique in allowing simultaneous prioritization of both dam removals and culvert replacements to enhance connectivity. A cumulative passability perspective is also lacking in most DSTs because all barriers are generally assumed to be absolutely impassable and therefore, any upstream length would be completely inaccessible. That viewpoint may be reasonable for dams but the enormous number of semi-passable road culverts (Martin and Apse 2011; Januchowski-Hartley et al. 2014) can only be analyzed properly if the combined likelihood of passing all downstream crossings to reach a focal barrier is estimated. Similarly, the benefits of a particular removal will often include fractional increases in the probability of stream access upstream of the focal barrier. Thus, we recommend adopting a cumulative passability approach in DSTs for aquatic connectivity.

Another key distinction among connectivity DSTs is whether they focus on upstream migration from large water bodies into river networks, or instead apply an alternate concept of connectivity that includes resident species that benefit from upstream and downstream movement (Diebel et al. 2014). Both perspectives can be analyzed using optimization models (O'Hanley and Tomberlin 2005; O'Hanley et al. 2013), but the approaches and implications should not be confused. Diadromous migrations from oceans and lakes into tributaries have a fixed polarity, which requires considering barriers in order from furthest downstream up to headwaters in order to understand available prospective habitat and restoration potential. This perspective lends itself well to connectivity visualization because accessibility remains static or decreases with distance upstream. In contrast, connectivity patterns for resident fishes can be more idiosyncratic along the length of a river because movement in any direction must be considered. The two ranking-based DSTs produced by The Nature Conservancy for the southeastern US and the Chesapeake Bay areas do allow users to choose between prioritizing for migratory or resident species; however, FishWerks and most others DSTs focus specifically on migratory fishes often in the context of diadromous life histories.

Any single DST cannot facilitate all aspects of all decisions, so it is important to be aware of the limitations of such tools. One key aim of our DST is to enable analysis of connectivity at both large and small scales. Ensuring data commensurability across a wide range of spatial scales sets the stage for coordinated decision making across the region to boost return on investment (Neeson et al. 2015) as well as addressing the needs of a broad range of stakeholders. However, it may also necessitate excluding higher-quality data that are not yet available for the entire geographic range covered by the tool. For example, we decided not to incorporate a handful of local barrier inventories that reveal additional road crossings because any analyses executed at a larger scale would be biased against these seemingly barrier-rich areas. More generally, some important features are simply infeasible to measure consistently across the region, such as the quality of spawning habitat in each reach, or the degree of local support for removal or repair of a particular barrier. These unmapped features vary widely and should certainly influence barrier removal decisions, illustrating the fact that no DST can fully replace the role of local knowledge in decision making processes.

As connectivity-focused DSTs are created for an increasing range of geographic and ecological contexts, an equally broad variety of designs is likely to emerge. Our experience coding and piloting the Great Lakes Connectivity DST, and our survey of other existing online tools, suggests that three issues merit special attention during DST design and maintenance. First, there is a need to ensure that the website and data remain up-to-date. Our crowd-sourcing approach remains experimental and requires ongoing oversight of user submissions and database updates. A static website, in contrast, may be dismissed by stakeholders because it has no mechanism to account for recent barrier removals and ongoing changes in the passability of aging structures.

A second key issue is that relatively few of the organizations interested in creating DSTs have the technical staff and infrastructure to support hosting and maintenance beyond a defined project period. Thus, the useful lifetime of a DST may be governed more by aging software and expired web-hosting contracts than diminished value to stakeholders. The more sophisticated the website, the more pieces of software that must be coordinated—including versions that are up-to-date and supported by their developers—and the more computing power must be available to run them. While FishWerks itself is not open source, the majority of the software components it relies upon are some variant of open source. A PostgreSQL database with a PostGIS extension for data storage and retrieval, a GeoServer installation for rendering of spatial data, and GDAL for minor manipulation of spatial data are all open source packages with well-established and thriving communities. In particular, a majority of them (PostGIS, GDAL, and GeoServer) are maintained by the Open Source Geospatial Foundation (OSGeo), which has over 1,000 active volunteers and was formed approximately 10 years ago. The fourth and only commercial product used in the DST is GAMS a proprietary optimization solver which is essential for executing models with the huge number of barriers across thousands of watersheds in the dataset. The integrated code that allows these software components to access the database and communicate with each other is specifically designed to be executed using dozens of parallel processors ensuring rapid analyses even during periods of high demand. Moreover, our DST interface is designed to be transferable to any server, allowing a partner organization to serve as a long-term host.

A final issue relates to raising awareness of DSTs and providing proper training to a diverse and ever-changing set of stakeholders. Creating anticipatory help tools and providing real-time support are time-consuming technical tasks. Potential users in agencies and non-profit organizations often turn over quickly, creating a constant need for training new personnel. Even more importantly, any DST is useless if stakeholders are not aware that it exists. Ideally, in the structured decision making process, stakeholders are involved early in the process to develop the problem and questions, and design a relevant and intuitive DST (Gregory and Keeney 2002; Miller et al. 2010). As additional stakeholders are identified, they can be integrated into the decision process. In our case, sequential funding sources have led to a series of expansions in the DST aims, elements, and stakeholder outreach efforts, but these developments have been facilitated by early decisions to include placeholders for desirable features in both the database and website. Throughout this 18-month process, our team has presented overviews of the DST to a wide range of Great Lakes audiences. Nonetheless, access records suggest that only a modest user base has developed despite considerable outreach efforts and diverse partnerships. Between 01 January 2015 and 01 June 2016, there were 5,139 users but on average they spent less than 2 minutes on the site and only 22% returned to FishWerks. Indeed, outreach and training may be the most profound challenges of creating a useful DST.

Ultimately, DSTs are only useful if they offer a set of visualization and analytical tools that significantly improves on simpler planning methods. Based on feedback we have received from stakeholders in numerous forums, the inherent complexity of aquatic connectivity planning warrants investment in developing, using, and maintaining a DST. Rising computing power, internet access speeds, and tech-savviness of stakeholders offer exciting opportunities to integrate additional ever more dimensions of the ecological, economic, and social dimensions of connectivity restoration. Simply put, optimization models and other powerful analytical tools are essential for understanding tradeoffs when confronted with numerous potential restoration projects that vary widely in terms of costs and benefits. Moreover, solutions produced by optimization models provide a good starting point for subsequent fine-tuning, via supplementary detailed analyses and consideration of hard to quantify social, political, and feasibility factors that can ultimately lead to the creation of a finalized, actionable recommendation. The current array of DSTs is sure to see increasing use, and we look forward to seeing how the next generation of tools will take shape.

Acknowledgments

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FIGURES

Figure 1: Barriers in Great Lakes basin included in the barrier removal optimization decision support tool. Dams are shown as black circles, road crossing culverts as small grey triangles.

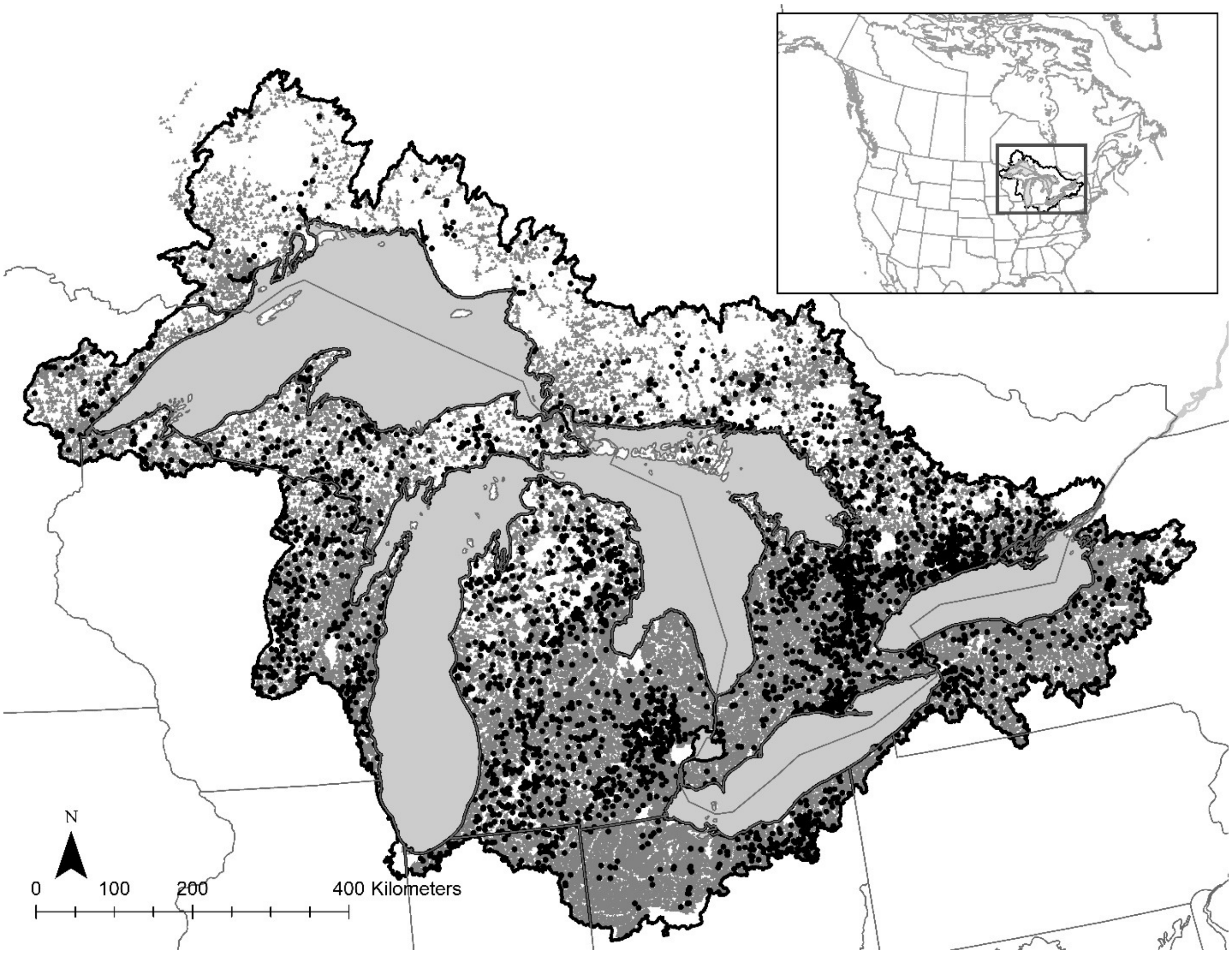
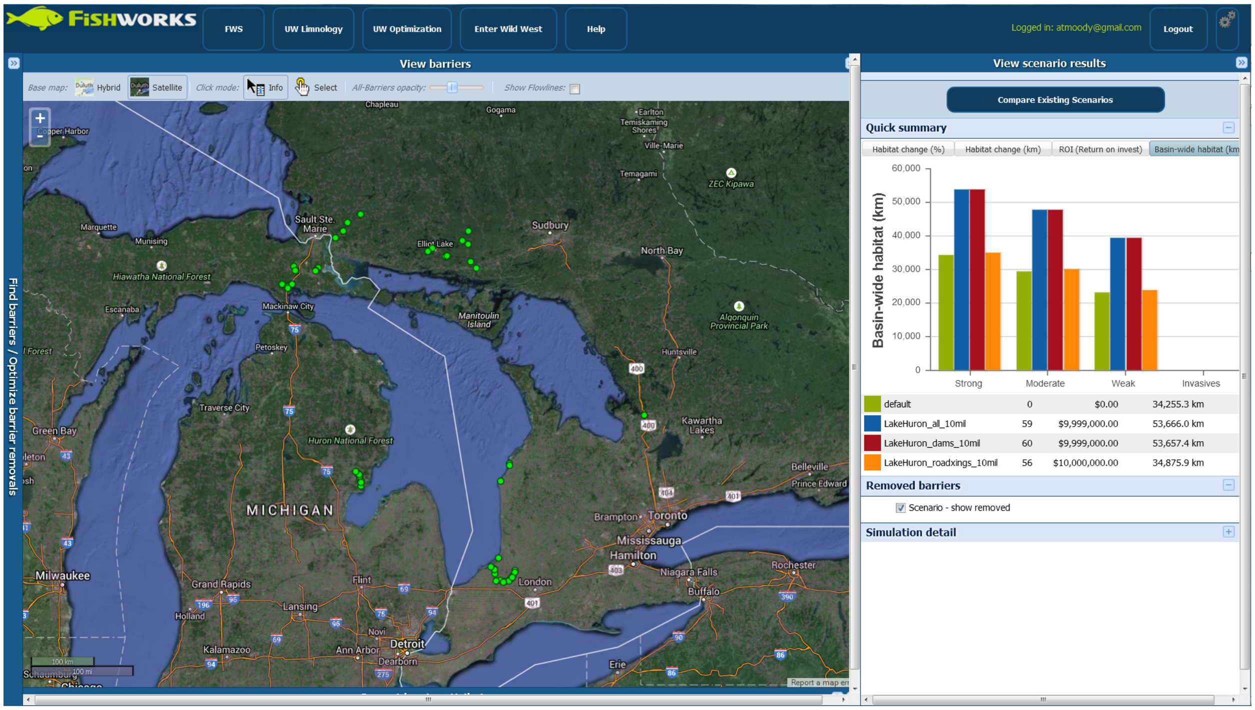


Figure 2: Comparing three barrier removal scenarios around Lake Huron with a $10 million budget: both dams and culverts considered for removal (blue bars in the graph to the right), only dams considered (red bars), and only road crossings considered (orange bars). Green bars show the initial amount of stream length available to migratory fishes prior to barrier removals. From left to right, the groups of four bars show results for fish species that are strong, moderate, and weak swimmers. Green dots on the map indicate the barriers recommended for removal in the culvert-only scenario (green bar).



🟩 default	0	$0.00	34,255.3 km
🟦 LakeHuron_all_10mil	59	$9,999,000.00	53,666.0 km
🟥 LakeHuron_dams_10mil	60	$9,999,000.00	53,657.4 km
🟧 LakeHuron_roadxings_10mil	56	$10,000,000.00	34,875.9 km

Removed barriers

☑ Scenario - show removed

Simulation detail

TABLES

Table 1: Swimming speeds of adults and swimming group assignment for migratory fishes in the Great Lakes Basin. Swim class is based on the following thresholds: strong ≥ 100 cm/s; 40 cm/s < moderate < 100 cm/s; weak ≤ 40 cm/s. Type: P = prolonged; B = burst; C = critical; W = critical water velocity.

Common name	**Scientific name**	**Swim class**	**Swimming speed (cm/s)**	**Substitute species**	**Reference**	**Type**
Lake Sturgeon	*Acipenser fulvescens*	Moderate	100		Peake 2008	W
American Eel	*Anguilla rostrata*	Weak	20		Peake 2008	W
Freshwater Drum	*Aplodinotus grunniens*	Moderate		Common Carp		
Quillback	*Carpiodes cyprinus*	Moderate		Common Carp		P
Longnose sucker	*Catostomus catostomus*	Moderate	62		Peake 2008	C
White Sucker	*Catostomus commersonii*	Moderate	62		Peake 2008	C
Lake Cisco	*Coregonus artedii*	Moderate	63		FishXing[1]	P
Lake Whitefish	*Coregonus clupeaformis*	Moderate	57		Peake 2008	C
Lake Chub	*Couesius plumbeus*	Weak	30			
Common Carp	*Cyprinus carpio*	Moderate	112		FishXing	P
Northern Pike	*Esox lucius*	Moderate		Tiger Musky	Webb et al. 1992	C
Muskellunge	*Esox masquinongy*	Moderate		Tiger Musky	Webb et al. 1992	P
Ruffe	*Gymnocephalus cernuus*	Weak		Yellow Perch		
Mooneye	*Hiodon tergisus*	Moderate				

Chestnut Lamprey	*Ichthyomyzon castaneus*	Weak		< Sea Lamprey		
N. Brook Lamprey	*Ichthyomyzon fossor*	Weak		< Sea Lamprey		
Silver Lamprey	*Ichthyomyzon unicuspis*	Weak		< Sea Lamprey		C
Channel Catfish	*Ictalurus punctatus*	Moderate				
Bigmouth Buffalo	*Ictiobus cyprinellus*	Moderate		White Sucker		
Black Buffalo	*Ictiobus niger*	Moderate		White Sucker		
Longnose Gar	*Lepisosteus osseus*	Moderate	51		Web et al. 1992	P
Burbot	*Lota lota*	Weak	39		Peake 2008	C
Smallmouth Bass	*Micropterus dolomieu*	Moderate	81		Peake 2004	P
White Perch	*Morone americana*	Moderate				
White Bass	*Morone chrysops*	Moderate				
Silver Redhorse	*Moxostoma anisurum*	Moderate		White Sucker		
Shorthead Redhorse	*Moxostoma macrolepidotum*	Moderate		White Sucker		
Greater Redhorse	*Moxostoma valenciennesi*	Moderate		White Sucker		
Round Goby	*Neogobius melanostomus*	Weak		Greenside Darter		
Spottail Shiner	*Notrophis hudsonius*	Weak				
Emerald Shiner	*Notropis atherinoides*	Weak				

Pink Salmon	*Oncorhynchus gorbuscha*	Strong	100		Peake 2008	W
Coho Salmon	*Oncorhynchus kisutch*	Strong	640		Bell 1991	B
Steelhead	*Oncorhynchus mykiss*	Strong	440		Bell 1991	P
Chinook Salmon	*Oncorhynchus tshawytscha*	Strong	304		Bell 1991	P
Rainbow Smelt	*Osmerus mordax*	Moderate		Brook Trout		
Yellow Perch	*Perca flavescens*	Weak	27		Nelson 1989	P
Channel Darter	*Percina copelandi*	Weak				
River Darter	*Percina shumardi*	Weak		Greenside Darter		P
Trout-Perch	*Percopsis omiscomaycus*	Weak	55		Jones et al. 1974	P
Sea lamprey	*Petromyzon marinus*	Moderate	79		Peake 2008	C
Round Whitefish	*Prosopium cylindraceum*	Moderate		Lake Whitefish		C
Longnose Dace	*Rhinichthys cataractae*	Moderate	62		Peake 2008	C
Brook Trout	*Salvelinus fontinalis*	Moderate	59		Peake 2008	C
Lake Trout	*Salvelinus namaycush*	Moderate	38		Peake 2008	C
Sauger	*Sander canadense*	Moderate		Walleye		
Walleye	*Sander vitreus*	Moderate	73		Peake et al. 2000	C

[1] Source: http://www.fsl.orst.edu/geowater/FX3/help/SwimData/Swim_Speed_Table.htm

Table 2: A representative list of decision support tools related to barrier removal and aquatic connectivity.

Barrier viewing	**Extent**	**Name**	**Type of barriers**
Static maps	Canada	Atlas of Canada	Hydropower-generating dams
	Connecticut River	Connecticut River Watershed Council	Dams
Web-based maps	Alaska	FishResourceMonitor	Culverts with fish passage ratings
	British Columbia	HabitatWizard	Dams and natural barriers
	California	Fish and Wildlife BIOS	Dams and culverts with high priority for removal
	Maine	Stream Habitat Viewer	Dams, culverts, and natural barriers
	Washington	WSDOT Fish Passage Barriers	Culverts with fish passage ratings
Downloadable GIS data	California	Passage Assessment Database (PAD)	14 different structure types including dams, culverts, natural barriers plus fish passage rating
	Canada	Atlas of Canada	Large dams
	Canada	CanFishPass	Fishways
	Massachusetts	Critical Linkages	Dams and culverts
	Northeast US	North Atlantic Aquatic Connectivity Collaborative	Dams and culverts
	Nebraska	Nebraska Dam Inventory	Dams

	Oregon	Oregon Fish Passage Barriers	Dams, culverts, and natural barriers, including fish passage rating
	United States	National Dams Inventory	Dams

Add-ons for evaluating connectivity in ArcGIS	**Extent**	**Name**	**Methodology**
	Aquatic	Barrier Analysis Tool (BAT)	
		CADSS	
		FIPEX	
		RivEX	
	Terrestrial	Conifor	Graph theory based
		CorridorDesigner	
		Linkage mapper	Circuit theory based
		MulTyLink	Optimization based

Barrier prioritization	**Extent**	**Name**	**Methodology**
Written guides	British Columbia		Scoring and ranking
	Northeast US	Northeast Aquatic Connectivity Project	Scoring and ranking
	United States	American Rivers	Cost-benefit analysis
	Washington	Barrier Assessment and Prioritization Manual	Scoring and ranking

Standalone software	Universal	OptiPass (formerly APASS)	Optimization but no map visualization capabilities
Web-based portal	Chesapeake Bay	Chesapeake Fish Passage Prioritization	Scoring and ranking
	Great Lakes	Great Lakes Connectivity Project	Optimization combined with map visualization
	Southeast US	Southeast Aquatic Connectivity Assessment Project	Scoring and ranking

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