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

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30 **ABSTRACT**

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

43

44 **INTRODUCTION**

45 Roughly 2,400 tributary rivers enter the Laurentian Great Lakes, creating one of the  
46 largest freshwater ecosystems in the world. These lakes and their watersheds provide recreation,  
47 jobs, and ecosystem services to 95 million people (Vaccaro and Read 2011; Allan et al. 2015;  
48 Campbell et al. 2015). In the services sector of the economy, which includes tourism, sport  
49 fishing, and boating, the net value of the lakes is estimated at \$2.7 trillion annually (Campbell et  
50 al. 2015). As the region has prospered, people have constructed dams in nearly every watershed,  
51 and culverts for road crossings are many times more abundant than dams. This infrastructure has  
52 fragmented fish habitat in Great Lakes tributaries (Januchowski-Hartley et al. 2013; Neeson et al.  
53 2015) affecting dozens of fish species. However, dams and road culverts also serve critical  
54 societal needs for power generation, flood control, transportation, and control of invasive species  
55 (e.g. Lavis et al. 2003; Stokstad 2010; Clarkson 2004; Novinger and Rahel 2003). This diversity  
56 of costs and benefits complicates decisions about restoring tributary connectivity for migratory  
57 fishes. Moreover, barrier management involves numerous governing bodies and interest groups  
58 whose priorities must be reconciled with regard to barrier removal or placement decisions.

59 Due to the dendritic nature of river networks, fragmentation is particularly problematic  
60 for migratory fishes; a single impassable barrier can prevent access to habitat in many different

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

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

85         The challenges within the Great Lakes region, as in many other settings, are three-fold.  
86 First, the lack of a centralized barrier database hampers spatial planning efforts particularly at  
87 large scales. Second, spatial contingencies among projects make it all but impossible to evaluate  
88 the costs and benefits of any one barrier removal project in isolation, necessitating the use of  
89 sophisticated computational approaches such as graph theory or optimization. Third, choosing  
90 among candidate projects necessarily involves navigating complex trade-offs between ecological  
91 and societal values that are incommensurable. For example, the potential ecological effects of

92 barrier removals could have both positive (via native species) and negative (via invaders and  
93 pathogens) consequences (McLaughlin et al. 2013), not to mention implications for human safety  
94 and recreation. Optimization models are ideally suited for dealing with these sorts of challenges.  
95 By explicitly accounting for interdependencies among decisions (e.g., the cumulative effect of  
96 multiple barrier removals on connectivity), they account for the benefits of coordinated actions to  
97 ensure the most efficient allocation of resources for restoration. Moreover, when applied to  
98 settings in which multiple objectives must be balanced, accessible optimization models enable  
99 decision makers to explore the consequences of alternative actions to clarify potential tradeoffs.

100

### 101 **Great Lakes Connectivity DST Development**

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

107

#### 108 *The science behind the tool*

109 The map of tributary streams used in the DST was created specifically for aquatic  
110 connectivity analyses (Diebel et al. In prep) and updates previous hydrography (Januchowski-  
111 Hartley et al. 2013, 2014; Neeson et al. 2015). The DST hydrography is a subset of the  
112 1:100,000-scale flowlines of the National Hydrography Database Plus Version 2 (NHD Plus V2  
113 2012) and Ontario Integrated Hydrology Dataset (OMNR 2013), pruned to the extent of the  
114 Great Lakes Aquatic Habitat Framework's synthetic drainage lines (Wang et al. 2015; Forsyth et  
115 al. In review). This hydrography dataset includes 2,404 tributaries, ranging from small coastal  
116 streams draining as little as 2.7 km<sup>2</sup>, to large rivers with thousands of km of total tributary length.  
117 The barrier layer currently includes 99,940 road crossings and 3,954 dams (Figure 1) but the  
118 exact number changes through user-contributed edits (details below). The barrier map improves  
119 on the previous version of our barrier database (Januchowski-Hartley et al. 2013, 2014; Neeson  
120 et al. 2015) because it is referenced to the updated DST hydrography and underwent additional  
121 barrier feature verification using aerial images. We do not currently account for natural barriers

122 (e.g., waterfalls and chutes), but will add these features as soon as spatially complete data on  
123 their locations is assembled.

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

134 Our barrier prioritization methodology is underpinned by two additional data types that  
135 have been previously published: the passability of road crossings (Januchowski-Hartley et al.  
136 2014), and the costs of dam removal or road crossing replacement to ensure full passage of  
137 migratory fishes (Neeson et al. 2015). Barrier passability is defined as the estimated proportion  
138 of fish able to pass through or over a barrier while migrating upstream (Kemp and O’Hanley  
139 2010). It can also be thought of as the probability that a given fish can successfully pass a  
140 particular barrier. Following Januchowski-Hartley et al. (2014), we used stream characteristics to  
141 model water velocity and outlet drops at road crossings. These modeled variables were translated  
142 into passabilities for three classes of fish with different swimming abilities (Table 1). The water  
143 velocity thresholds for these swimming classes were 0.4 m/s (weak swimmers), 0.7 m/s  
144 (moderate swimmers), and 1.0 m/s (strong swimmers). Each species was assigned to a class  
145 based on swimming speeds reported in the literature when possible or based on expert opinion  
146 when necessary. We calculated the cost of removing dams based on an analysis of completed  
147 dam removals in the Great Lakes basin (see Neeson et al. 20015 for a discussion of model fit and  
148 data limitation), while the cost of replacing a culvert was estimated from stream size, material,  
149 labor costs, and road characteristics (Neeson et al. 2015).Our model focuses on barrier removal  
150 rather than alternative means of restoring passability (e.g., installing fish ladders or elevators)  
151 because of the complexity of estimating initial and recurring costs for these mitigation options.

152

153 **DST Structure and Features**

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

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

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

206 After an optimization analysis is complete, the map displays the location of all barriers  
207 included in the optimal portfolio of barrier removals and graphical summaries of the results  
208 appear. The graphs display the cumulative stream length expected to be gained from the optimal  
209 portfolio of barrier removals including tributary channel made accessible (absolute length or  
210 percent change), and the associated return on investment (channel length per dollar). The map of  
211 barriers suggested for removal is displayed onscreen, and a list of barriers and their associated  
212 attributes can be exported as a CSV file. To facilitate comparisons among alternative budgets or



213 sets of ignored/removed barriers, registered users can also save model results to create graphs  
214 comparing multiple analyses.

215

## 216 **Example applications**

217 Maximizing restoration efficiency at large spatial scales. The return on investment from barrier  
218 removals generally increases with the size of the area analyzed because more options can be  
219 considered simultaneously, thus boosting the likelihood of identifying high-return, low-cost  
220 removals, as well as synergistic removals within the same watershed. For instance, with a  
221 generous budget of \$100 million, optimizing removals over the entire Great Lakes Basin  
222 suggests the potential to double the length of stream accessible to migratory fishes, whereas  
223 separate optimizations for each tributary yields only a 14% increase in fish habitat (Neeson et al.  
224 2015). Even at a state-level, our optimization analysis tool can rapidly suggest a coordinated  
225 portfolio of projects that increases potential fish habitat far more than selecting projects based on  
226 their individual merits.

227

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

235

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

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

247

## 248 **CONCLUSION**

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

264 Another key distinction among connectivity DSTs is whether they focus on upstream  
265 migration from large water bodies into river networks, or instead apply an alternate concept of  
266 connectivity that includes resident species that benefit from upstream and downstream  
267 movement (Diebel et al. 2014). Both perspectives can be analyzed using optimization models  
268 (O’Hanley and Tomberlin 2005; O’Hanley et al. 2013), but the approaches and implications  
269 should not be confused. Diadromous migrations from oceans and lakes into tributaries have a  
270 fixed polarity, which requires considering barriers in order from furthest downstream up to  
271 headwaters in order to understand available prospective habitat and restoration potential. This  
272 perspective lends itself well to connectivity visualization because accessibility remains static or  
273 decreases with distance upstream. In contrast, connectivity patterns for resident fishes can be  
274 more idiosyncratic along the length of a river because movement in any direction must be

275 considered. The two ranking-based DSTs produced by The Nature Conservancy for the  
276 southeastern US and the Chesapeake Bay areas do allow users to choose between prioritizing for  
277 migratory or resident species; however, FishWerks and most others DSTs focus specifically on  
278 migratory fishes often in the context of diadromous life histories.

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

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

302 A second key issue is that relatively few of the organizations interested in creating DSTs  
303 have the technical staff and infrastructure to support hosting and maintenance beyond a defined  
304 project period. Thus, the useful lifetime of a DST may be governed more by aging software and  
305 expired web-hosting contracts than diminished value to stakeholders. The more sophisticated the

306 website, the more pieces of software that must be coordinated—including versions that are up-to-  
307 date and supported by their developers—and the more computing power must be available to run  
308 them. While FishWerks itself is not open source, the majority of the software components it  
309 relies upon are some variant of open source. A PostgreSQL database with a PostGIS extension  
310 for data storage and retrieval, a GeoServer installation for rendering of spatial data, and GDAL  
311 for minor manipulation of spatial data are all open source packages with well-established and  
312 thriving communities. In particular, a majority of them (PostGIS, GDAL, and GeoServer) are  
313 maintained by the Open Source Geospatial Foundation (OSGeo), which has over 1,000 active  
314 volunteers and was formed approximately 10 years ago. The fourth and only commercial product  
315 used in the DST is GAMS a proprietary optimization solver which is essential for executing  
316 models with the huge number of barriers across thousands of watersheds in the dataset. The  
317 integrated code that allows these software components to access the database and communicate  
318 with each other is specifically designed to be executed using dozens of parallel processors  
319 ensuring rapid analyses even during periods of high demand. Moreover, our DST interface is  
320 designed to be transferable to any server, allowing a partner organization to serve as a long-term  
321 host.

322         A final issue relates to raising awareness of DSTs and providing proper training to a  
323 diverse and ever-changing set of stakeholders. Creating anticipatory help tools and providing  
324 real-time support are time-consuming technical tasks. Potential users in agencies and non-profit  
325 organizations often turn over quickly, creating a constant need for training new personnel. Even  
326 more importantly, any DST is useless if stakeholders are not aware that it exists. Ideally, in the  
327 structured decision making process, stakeholders are involved early in the process to develop the  
328 problem and questions, and design a relevant and intuitive DST (Gregory and Keeney 2002;  
329 Miller et al. 2010). As additional stakeholders are identified, they can be integrated into the  
330 decision process. In our case, sequential funding sources have led to a series of expansions in the  
331 DST aims, elements, and stakeholder outreach efforts, but these developments have been  
332 facilitated by early decisions to include placeholders for desirable features in both the database  
333 and website. Throughout this 18-month process, our team has presented overviews of the DST to  
334 a wide range of Great Lakes audiences. Nonetheless, access records suggest that only a modest  
335 user base has developed despite considerable outreach efforts and diverse partnerships. Between  
336 01 January 2015 and 01 June 2016, there were 5,139 users but on average they spent less than 2

337 minutes on the site and only 22% returned to FishWerks. Indeed, outreach and training may be  
338 the most profound challenges of creating a useful DST.

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

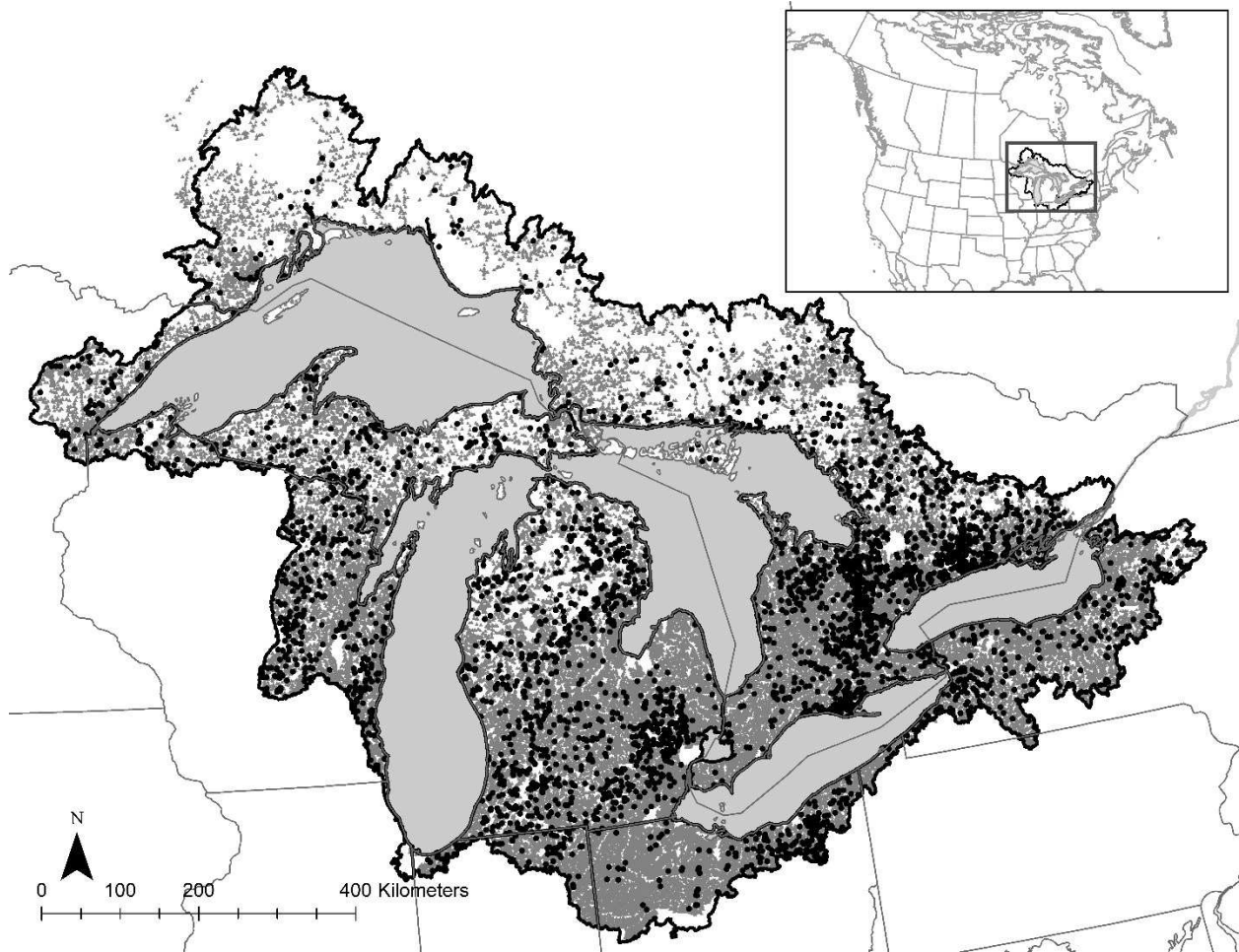
353

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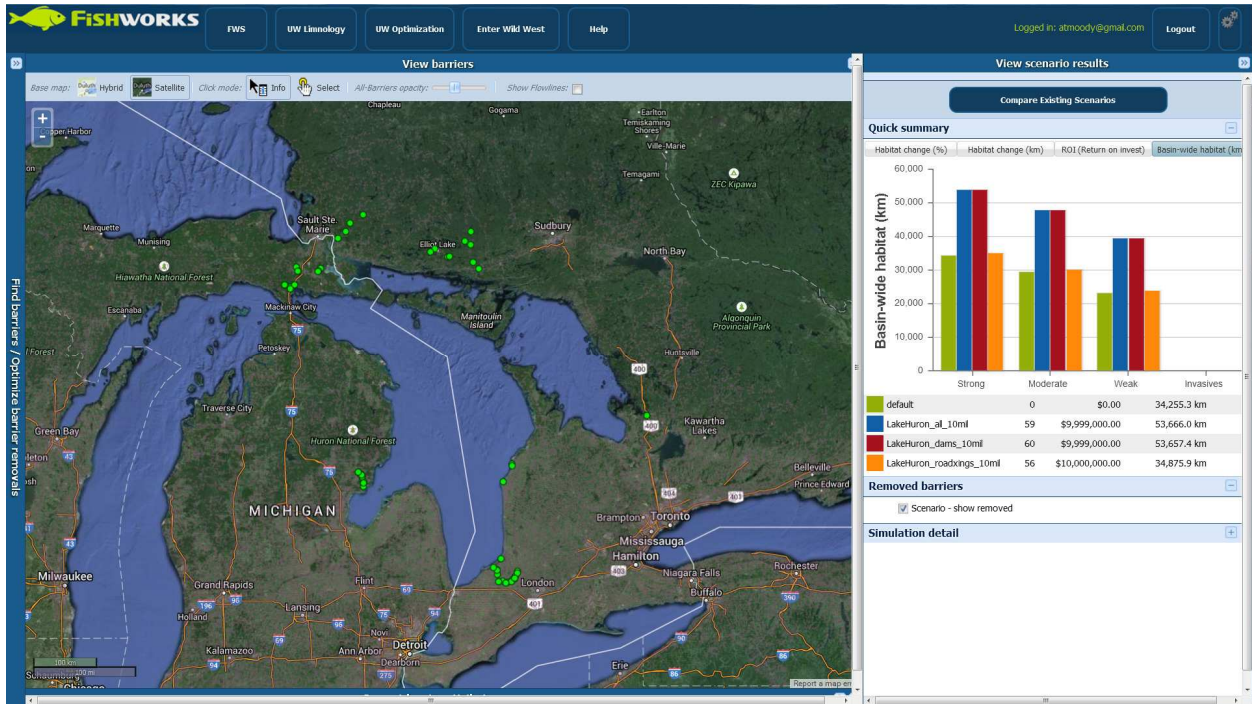
363 **FIGURES**

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



366  
367

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



375

376 **TABLES**

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

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



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

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

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381 <sup>1</sup>Source: [http://www.fsl.orst.edu/geowater/FX3/help/SwimData/Swim\\_Speed\\_Table.htm](http://www.fsl.orst.edu/geowater/FX3/help/SwimData/Swim_Speed_Table.htm)

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

<b>Barrier viewing</b>	<b>Extent</b>	<b>Name</b>	<b>Type of barriers</b>
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
<b>Add-ons for evaluating connectivity in ArcGIS</b>	<b>Extent</b>	<b>Name</b>	<b>Methodology</b>
	Aquatic	Barrier Analysis Tool (BAT) CADSS FIPEX RivEX	
	Terrestrial	Conifor CorridorDesigner Linkage mapper MulTyLink	Graph theory based  Circuit theory based Optimization based
<b>Barrier prioritization</b>	<b>Extent</b>	<b>Name</b>	<b>Methodology</b>
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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