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Aging infrastructure creates opportunities for cost-efficient restoration of aquatic ecosystem connectivity

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Abstract

A hallmark of industrialization is the construction of dams for water management and roads for transportation, leading to fragmentation of aquatic ecosystems. Many nations are striving to address both maintenance backlogs and mitigation of environmental impacts as their infrastructure ages. Here, we test whether accounting for road repair needs could offer opportunities to boost conservation efficiency by piggybacking connectivity restoration projects on infrastructure maintenance. Using optimization models to align fish passage restoration sites with likely road repair priorities, we find potential increases in conservation return-on-investment ranging from 17% to 25%. Importantly, these gains occur without compromising infrastructure or conservation priorities; simply communicating openly about objectives and candidate sites enables greater accomplishment at current funding levels. Society embraces both reliable roads and thriving fisheries, so overcoming this coordination challenge should be feasible. Given deferred maintenance crises for many types of infrastructure, there could be widespread opportunities to enhance the cost-effectiveness of conservation investments by coordinating with infrastructure renewal efforts.

Keywords: Infrastructure, connectivity, fragmentation, conservation, restoration, coordination, collaboration

Introduction

Roads and dams blanket industrialized landscapes around the world. Such infrastructure has a host of local and long-distance effects on the natural environment, including contributing to extensive fragmentation of terrestrial and freshwater ecosystems (Saunders et al. 1991, Trombulak and Frissell 2000, Doyle and Havlick 2009). While infrastructure is essential for the functioning of modern economies, there is growing societal commitment to minimizing and mitigating its environmental impacts. Here, we explore how planned infrastructure maintenance could provide opportunities to increase the cost-effectiveness of conservation investments in restoring the connectivity of aquatic ecosystems.

The life cycle of infrastructure offers three stages of opportunities to mitigate environmental impacts by adhering to recognized best practices: during site selection and initial planning, design and construction; during routine operations and maintenance; and during decommissioning, when economic and safety concerns typically have primacy (Doyle and Havlick 2009). The prevalence of each type of opportunity varies geographically. In developing nations, most infrastructure spending supports new construction, hence conservation opportunities will be associated with designing projects to minimize their impacts (Dulac 2013; Laurance et al. 2014; Mandle et al. 2016). In industrialized nations of North America, Europe and Australasia, however, nearly all infrastructure spending supports the maintenance and occasional decommissioning of existing structures (Doyle et al. 2008; Doyle and Havlick 2009). This pattern is likely to hold for the foreseeable future, such that opportunities to align conservation and infrastructure objectives will arise largely in the context of addressing maintenance backlogs and strategic decommissioning. For example, more than $2 trillion of repair costs are anticipated for U.S. infrastructure given its current condition (ASCE 2017), and the US Forest Service has identified almost 300,000 km of roads that may be decommissioned in the next 40 years (Ihara et al. 2003). The massive, ongoing investments required to sustain acceptable infrastructure dwarfs budgets for conserving the environment and natural resources (Lederman and Waches 2016), potentially creating widespread incentives for conservation groups to collaborate with infrastructure agencies. From the conservation perspective, a promising strategy is to identify high-return efforts that leverage already-funded infrastructure maintenance and decommissioning projects (White 2014).

To explore the efficiencies that could be achieved through collaborative approaches, we focus on the conservation challenge of restoring aquatic ecosystem connectivity by enhancing the passability of dams and road crossings to riverine animals. River fragmentation is a global problem due to the thousands of large dams that act as absolute barriers in river networks worldwide (Grill et al. 2015). While dams are often a focus of high-profile decommissioning efforts, road crossings are many times more numerous (Januchowski-Hartley et al. 2013) and their aggregate contribution to fragmentation is substantial (Jackson 2003; Neeson et al. 2015; McKay et al. 2016). Mitigation of the ecological impacts of road crossings typically occurs by replacing impassable culverts with fish-friendly designs (Cenderelli et al. 2011). Though larger culverts have greater initial costs, their greater diameter reduces failure rates and maintenance costs associated with debris removal (Gillespie et al. 2014). As a result, the higher installation costs of larger culverts may be offset over the lifespan of the structure, yielding societal and economic benefits. Thus, transportation agencies are increasingly amenable to up-sizing or otherwise adjusting culvert designs to maximize the resilience of road infrastructure to greater peak streamflow arising from the changing climate, and to enhance aquatic organism passage (Schall et al. 2012). As these agencies confront a growing backlog of maintenance demands, they may welcome partnerships that broaden support for climate-appropriate and nature-friendly designs of transportation infrastructure.

A piggybacking approach for restoring aquatic connectivity might entail a conservation organization paying for a fish-friendly design upgrade at a site where a transportation agency was already planning to remove and replace an aging culvert. In this example, the conservation group would bear only a fraction of the cost of the full project, because the infrastructure agency had already budgeted for the base costs of labor and materials for culvert replacement and road resurfacing to fulfill its own mission. Though piggybacking strategies have the potential to offer high conservation benefit at little cost, efficient pursuit of this approach at a large scale requires systematic information on the costs and benefits of thousands of potential projects that can be analyzed using sophisticated planning tools. A challenging step in this process is maintaining dialogue and data exchange between conservation organizations and infrastructure agencies so that each understands the other's priorities and capacities.

Here, we use spatial data on road surface condition in the US state of Michigan to evaluate the potential benefits for conservation practitioners of piggybacking their fish passage investments on road maintenance projects. First, we use an optimization model to calculate the return-on-investment (ROI), measured in terms of the river length reconnected per dollar spent, that could be achieved by a conservation organization paying the full cost of high-priority culvert replacements. We then use road surface condition data as a proxy for future investment by infrastructure agencies in road maintenance projects, and calculate site-specific reductions in costs to implement fish-friendly culverts when conservation investments take advantage of these leveraging opportunities. By comparing the ROIs from the full cost and piggybacking models, we calculate the savings that would be possible by aligning conservation investments with upcoming infrastructure maintenance.

Methods

To predict future road maintenance, we obtained road surface condition data for 781,407 road segments (totaling 2.33×10^5 km of road length) for the years 2004 to 2013 from the Michigan Department of Transportation (MDOT). Road surface condition is scored using the Pavement Surface Evaluation and Rating system (PASER), a categorical system in which roads receive scores from 10 (perfect condition) to 1 (very poor). In general, roads ratings ≥8 require no maintenance, ratings of 5 - 7 would benefit from preventative maintenance, while ratings ≤4 require structural improvement, resurfacing or complete reconstruction (Fig. 1).

The MDOT PASER data is the most comprehensive spatial information on road conditions for Michigan, yet only a portion of the road network is surveyed in any given year. To estimate the 2013 rating of segments that were last surveyed in an earlier year, we created a state transition model describing road degradation rates (Appendix A). While the state does maintain a PASER data set for the federal aid, paved road network (approximately 1/3 of the entire public road mileage), information on the remaining 2/3 of the Michigan public road network is managed by individual counties and municipalities. These data are not fully complete at a state level, so we assumed that, on average, these roads would be in similar condition to those in the state database. Thus, we assigned ratings to these crossings by randomly sampling from the distribution of scores in the state PASER database. Repeating the randomized scoring process 30 times indicates that our ROI results are robust to that uncertainty; the coefficient of variation in habitat gains was just 4.62%.

We estimated the costs that a conservation group would pay for a culvert upgrade project under two different cost-sharing strategies (Fig. 1). First, we assumed that any road crossing with a PASER score of 4 or lower would be repaved by the road agency in the near future, including paying the full cost to replace culverts using a hydraulic design adequate to handle flows with a 50-year recurrence interval (MDOT 2009). Conservation organizations could then elect to pay for the cost difference to upgrade from the hydraulic design to a culvert with state-of-the-art features for aquatic organism passage (AOP) to achieve maximal fish passage. For roads with a PASER score of 5 or higher, MDOT is assumed to be unlikely to sponsor any road work in the near future. Thus, conservation organizations would bear the full cost of the culvert replacement, including all excavation and resurfacing costs, if such projects were pursued. Hereafter, we refer to this as the "top-up" cost-sharing strategy, in reference to the idea that conservation groups could elect to top-up infrastructure spending on low-condition culverts to ensure full fish passage.

Our second cost-sharing strategy is a "discounting" model under which the road agency would be willing to make a partial contribution toward the replacement costs for any culvert, given the benefits of having an upgraded culvert. Specifically, we assumed that the road agency's fractional contribution to total costs would be inversely proportional to the current PASER score: (10 – Score) / 10. The discounting strategy would allow conservation organizations to realize some savings when selecting culverts of high connectivity value even when the overlying pavement is in good condition, but would require greater coordination and negotiation with the road agency because the final portfolio would reflect conservation priorities alone.

For both the top-up and discounting cost-sharing strategies, we estimated the full cost of culvert replacement under a hydraulic design using an updated version of the model in Neeson et al. (2015). The model accounts for costs related to stream size, road width, and surface type. We then explored three different methods for estimating the costs of AOP culvert designs. In the first method, AOP cost is treated as a linear function of the cost a hydraulic design, specifically a 21% surcharge (hereafter, the “linear” cost model). The 21% surcharge estimate represents the average increase in project costs across studies of completed culvert projects (Levine 2013). In the second method, we assumed that the AOP design would entail installing a structure that could pass a bankfull flow (hereafter, “BFW” cost model), and based cost on empirical estimates of replacement components, including culvert structure, fill, road replacement, and labor. Cost components were derived from the Michigan Department of Transportation’s 2015 schedule of pay items (https://mdotjboss.state.mi.us/BidLetting/BidLettingHome.htm). The width of each structure is equal to the estimated bankfull width of the stream based on a drainage area regression (Wilkerson et al. 2014). Structure types were determined by road type and stream bankfull width; interstate, highway, and urban roads use concrete structures, rural roads use metal structures, and all crossings use the lowest cost structure that meets material and size requirements. Because the BFW cost model often entailed switching to a different class of structure (e.g., changing from a steel culvert to a concrete arch), AOP costs under the BFW model were on average 221% of hydraulic costs. In the third method, termed a “compromise” model, we used recent MDOT pay items to estimate the cost of maximizing culvert diameter (up to bankfull through-flow) within the same class of structure. On average, AOP costs under the compromise model were estimated as 139% of hydraulic costs. Our exploration of three distinct cost models (linear, BFW, and compromise) reflects our inability to determine a priori which culvert design would be adequate for restoring full passability.

To quantify the cost savings that might be achieved by a conservation organization that aligns its investments with road maintenance priorities, we used an optimization framework to compare return-on-investment for fish passage projects under the two cost-sharing strategies (top-up, and discounting) and calculated these cost savings for each of the three estimates of AOP project costs (linear, BFW, and compromise AOP cost models). We focused on the Saginaw River watershed, the largest watershed in Michigan and one that is fragmented by 4,918 road crossings and 153 dams. The average PASER scores for this watershed (5.024) are very close to the average for all of Michigan (5.01; t-test $p > 0.05$); thus, the proportion of road culvert projects with opportunities for cost-sharing in the Saginaw River basin is broadly representative of opportunities across the state.

We evaluated ROI for each of two distinct restoration targets: connectivity for stream-resident fishes versus connectivity for lake-migrant fishes. To address the first case, we developed an optimization model that selects a portfolio of projects to maximize a common index of within-watershed connectivity (dendritic connectivity index, DCI; see Appendix B). To address the second case, we employed the optimization model from Neeson et al. (2015) that selects a portfolio of projects to maximize the total length of stream miles that are accessible to fishes migrating from the Great Lakes toward headwater breeding habitats. In general, the second target directs focus to barriers low in a watershed, while the first emphasizes expansion of fully-connected habitat anywhere in the watershed. For both optimization models, we estimated the current passability of each road culvert following Januchowski-Hartley et al.

(2014), and assumed that installation of an AOP-design culvert would restore full passability. For both optimization models, we explored increases in stream connectivity that could be achieved under budgets ranging from $5M to $30M. These budget levels are on par with recent investments in stream connectivity in the region (Moody et al. 2017).

While our estimates of barrier cost, passability and upstream river length are based on the best available spatial data sets, these estimates have not been validated with on-the-ground surveys. Accordingly, we performed a sensitivity analysis to quantify the degree to which model outputs might depend on uncertainty in the underlying data. Overall, we found that the benefits of cost-sharing were relatively insensitive to variation in estimates of barrier cost, passability, and upstream river length (see Appendix C for details).

Results

State-wide, road surface condition on Federal aid eligible roads in Michigan declined dramatically from 2004 to 2013 (Fig. 2A), highlighting a growing maintenance backlog. In 2004, for example, only 10.5% of road segments had a PASER rating of 4 or lower; by 2013, this number had risen to 36%, meaning that 1 out of 3 road segments was in need of significant reconstruction work in the coming years. These poor condition road crossings are equally prevalent from headwaters to river outlets, indicating restoration opportunities throughout river networks (Fig. 2B).

Aligning priorities for aquatic connectivity restoration with impending infrastructure maintenance can dramatically increase conservation return-on-investment. In the Saginaw River basin, this effect is greatest in the case of restoring connectivity for stream-resident fishes (Fig.

3A). An optimal investment of $30M prioritized without regard to cost-sharing opportunities, for example, would result in a 1321% increase in the DCI score for resident fishes. Investing the same $30M using a piggybacking approach under the linear AOP cost model, however, would result in a 1652% increase (under the top-up cost-sharing strategy) or 1541% increase (under the discounting cost-sharing strategy) in DCI (Fig. 3B). Therefore, ROI can be enhanced by piggybacking by up to 25% (i.e., increased from 1321% gain to 1652% gain) compared to the traditional funding model in which conservation organizations pay the full cost of their priority projects.

The ROI gains from piggybacking depend strongly on the method used to estimate costs of culvert materials to ensure aquatic organism passage. The BFW cost model offered only marginal improvements to ROI from piggybacking, in contrast to the linear cost model (Fig. 3B). The compromise cost model offered moderate improvements in cost-efficiency to achieve AOP.

Selecting fish passage projects based on future road maintenance alters the number, but not watershed position, of projects prioritized to enhance connectivity for stream-resident fishes. Most of the 4,918 road crossings in the Saginaw River occur on small 1^{st} and 2^{nd} order streams, while relatively few occur on the Saginaw mainstem (5^{th} – 7^{th} order) (Fig. 3C). When conservation organizations pay the full cost of culvert replacements (no cost-sharing), the optimal investment of $30 M involves 1,091 road crossings and 42 dams (1,133 projects in total; Fig. 3D). Under a top-up cost-sharing strategy, however, the optimal investment of $30 M includes many more projects: 1,936 road crossings and 45 dams (1,981 projects in total; Fig. 3C). Under a discounting cost model, the optimal investment of $30 M comprises 1,600 road crossings and 45 dams. Under all three selection scenarios, priority projects are disproportionately located on 2^{nd} order reaches (Fig. 3C-3D).

When optimizing for Great Lakes migratory fishes, the benefits of cost-sharing were smaller than for stream-resident fishes, yet still considerable. With a budget of $30M, for example, a top-up cost-sharing strategy offered up to 14% gain in ROI for migratory fishes (Fig. 4A), less than the 25% gain for stream-resident fishes (Fig. 3A). Though project selection for migratory fishes is necessarily more constrained because downstream barriers must be removed first, optimal project portfolios for both stream-resident and migratory fishes contained roughly similar proportions of road crossings and dams (Fig. 4B). Thus, while increasing habitat access for Great Lakes migratory fishes requires the removal of dams low in the watershed, the decrease in benefits of cost-sharing for migratory fishes in this watershed was not due to greater spending on dams overall.

Although optimal project selection under cost-sharing scenarios generally favors replacement of road crossings that already require urgent maintenance, some projects are so beneficial that conservation organizations should consider bearing the full cost. To maximize DCI under a top-up cost model, for example, the optimal investment of $30M includes 1,323 road crossings in poor condition, but also 613 road crossings in moderate to good condition. These 613 projects are high-cost, high-reward projects that merit consideration despite lack of cost-sharing opportunities. Optimal project selection for migratory fishes is similarly diverse. For an investment of $30M under the top-up model, the best portfolio includes 1,430 road crossings in poor condition, 756 full-cost road crossings (moderate to good condition), and 45 dams.

Discussion

We find that aligning restoration investments with infrastructure maintenance can increase return-on-investment for conservation purposes by up to 25%. Given the maintenance backlog in Michigan (Fig. 2) and throughout the US (ASCE 2017), there should be abundant opportunities to implement similar strategies in the coming years. Furthermore, piggybacking strategies could be coupled with strategic decommissioning of dams (Doyle et al. 2003; Stanley and Doyle 2003; Fitzpatrick and Neeson 2018), thereby leveraging societal responses to the problem of aging infrastructure in ways that enhance access of migratory fishes to river networks that are currently highly fragmented.

It is striking that opportunities to leverage infrastructure maintenance to boost conservation ROI are much greater for stream-resident fishes than for migratory species in our case study. This is due to differences in the role of the river network structure in constraining project selection. For migratory fishes, little habitat gain is possible without first removing expensive dams that occur low in the watershed (Kemp and O'Hanley 2010, McLaughlin et al. 2013). As a consequence, Great Lakes migratory fishes fail to benefit from most of the low-cost piggybacking opportunities for culvert replacement because expensive downstream dams remain in place, thereby constraining overall ROI. In contrast, for stream-resident fishes, optimal project selection is less constrained by any one barrier, enabling conservation organizations to take advantage of a wider range of piggybacking opportunities throughout the watershed. This disparity would be amplified when analyzing multiple watersheds because the terminal dam challenge is ubiquitous, but enlarging the set of potential road crossings that would increase in-stream connectivity raises the odds of identifying high-return project sites.

Average PASER scores for the Saginaw River watershed are nearly identical to the Michigan-wide average, suggesting that the conservation efficiencies demonstrated here can be replicated throughout the state. Presumably, the opportunities for conservation piggybacking scale directly with the proportion of road segments that have poor pavement condition, such that transportation agencies are amenable to cost-sharing. Our models also depend on several key assumptions that we could not verify: that roads with and without PASER data are comparable in condition and repair costs, and that road resurfacing in response to a low PASER score is always accompanied by culvert replacement (typically, the design life of culverts is longer than that of pavements). In general, roads without PASER data are in worse condition than the Federal aid eligible roads analyzed here (MTAMC 2010); thus, the potential for conservation efficiencies in the full road network should be even greater. Furthermore, part of the cost-efficiencies demonstrated here would apply even if cost-sharing was limited to conservation organizations paying the entire cost of culvert replacement to match pavement resurfacing by transportation agencies.

Our analysis also omits other key factors that influence the conservation value of a particular barrier removal: the presence of natural barriers to fish movement, the potential for facilitating invasive species (McLaughlin et al. 2013, Neeson et al. 2016; Milt et al. in press) and pathogens (Hurst et al. 2012), or impacts to the social and cultural ecosystem services associated with impoundments (Fox et al. 2016, Magilligan et al. 2017). Furthermore, conservation objectives and priority species vary widely among decision-makers across the region (Allan et al. 2013, Pearsall et al. 2013, Neeson et al. in press). While consideration of these factors is essential for evaluating individual barrier removal projects, our sensitivity analysis (Appendix C) suggests that the benefits of cost-sharing overall will be robust to changes in the costs and benefits of particular barrier removals.

Though our analysis focused on the benefits of cost-sharing for conservation outcomes, AOP culvert designs could provide long-term savings to transportation agencies as well. Though AOP culverts have higher upfront cost, their greater diameter enables them to pass water and debris associated with larger floods, reducing failure rates and maintenance needs (Gillespie et al. 2014, O'Shaughnessy et al. 2016). Thus, the installation costs may ultimately be fully offset over the lifespan of the structure. However, the greater upfront costs of AOP culverts are often prohibitive for transportation agencies in a restricted budget climate (O'Shaughnessy et al. 2016). The cost-sharing strategies outlined here offer a rationale for conservation organizations to contribute to these upfront costs, providing benefits to both natural resource management (increased ecosystem connectivity) and transportation (greater flood resilience and lower long-term costs) interests. Importantly, these parallel benefits occur without sacrificing infrastructure maintenance priorities or demanding additional conservation funds, thereby representing a true win-win scenario.

Our work offers a model for large-scale coordination of conservation and infrastructure investments. There is growing recognition of the potential role of such joint efforts, and some piggybacking of project costs already occurs opportunistically (White 2014). For example, state transportation agencies are typically required by law to vet construction plans with state wildlife agencies (Public Law 109-59 2005). Thus, key relationships may already be in place, but piecemeal, opportunistic collaborations are much less efficient than coordinated portfolios of projects for ecological restoration (Neeson et al. 2015). Knowledge-sharing between conservation and infrastructure organizations also may be challenging due to differences in culture, data management protocols, jurisdictional boundaries, and perceived interests. In the case of aquatic connectivity, spatial data on road surface and culvert condition is often managed at the county or municipality level, whereas dam assessments are typically performed by state or federal agencies. The increasing availability of sophisticated optimization approaches in both conservation and infrastructure sectors may provide a platform for data integration and strategic planning to align priorities to mutual benefit (Moody et al. 2017). Indeed, in some states, legislation already mandates consideration of aquatic organism passage during construction or repair of road culverts (Levine 2013; Gillespie et al. 2014).

Successful implementation of cost-sharing strategies over the long term (i.e., 10 to 30+ years) will require coordination of multiple rounds of investment by conservation and infrastructure groups. In the short term (i.e., within several years), scheduling is less critical. Our analysis focuses on identifying restoration opportunities that may exist in a particular year (2015), but it should be possible to spread conservation investments over several years. For example, investing $10M per year over three years would yield the same conservation benefits as a single lump-sum investment of $30M. The one caveat is that investments in any one year must be large enough to afford any project within the portfolio; otherwise, annual budgets constrain project selection and it may not be possible to afford certain high-cost, high-reward projects (Neeson et al. 2015). In the Saginaw River this is not likely to be an important constraint, because more than 99% of barrier removal projects cost less than $500k. Ultimately, successful long-term implementation of the cost-sharing strategies in our paper will require at least annual updating of shared databases to identify cases where further deterioration of roads has created new cost-sharing opportunities, or where the completion of construction projects has eliminated some cost-sharing opportunities.

A key remaining hurdle involves spatial road and culvert condition data: in many states, collection of information on road surface and culvert condition on the local road system is the prerogative of the county and municipality that owns the road. In many cases the agency may not collect this type of data. Furthermore, in states outside of Michigan, it is uncommon for road and culvert condition data to be collected on both the state and local systems using a uniform rating system. The lack of data and the non-uniformity of data that is collected greatly adds to the complexity of this planning. Furthermore, the differences among the three methods for estimating AOP structure costs and their consequent influence on ROI indicate that more work is needed to better understand the relative costs of various designs.

In the context of expanding rather than repairing infrastructure, habitat conservation plans (HCPs; Lederman and Wachs 2014) offer another example of the benefits of jointly considering transportation needs and ecosystem outcomes. HCPs arose as a cost-effective means of complying with Endangered Species Act (ESA) mandates by preemptively seeking input from environmental management agencies. For large infrastructure projects, such dialogue early in the planning process may create opportunities for effective action as well as financial leveraging. The funding streams associated with transportation and other infrastructure investments dwarf those earmarked for environmental management (Lederman and Wachs 2016), creating an incentive for genuine engagement by conservation organizations.

Infrastructure is integral to modern societies yet also creates pervasive environmental stress in ecosystems worldwide, calling for innovative approaches to maintaining its benefits and mitigating its impacts. Given the looming need for large-scale infrastructure investments in much of the developed world, cost-sharing strategies offer an appealing means for advancing both conservation and transportation interests. Our study highlights the potential benefits from both perspectives, and underscores the opportunities for cost-effective restoration that could arise from increased data-sharing and collaboration during infrastructure project planning.

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Figure legends

Figure 1: Illustration of cost-sharing strategies for road culvert replacements based on road surface condition scores of 8 (top panel), 5 (middle) and 2 (bottom panel). The horizontal red line shows the cost of a hydraulic designed culvert project, which is on average 83% of the cost of an Aquatic Organism Passage (AOP) designed culvert project. When no cost-sharing occurs, the conservation group pays the full cost of an AOP designed culvert project regardless of road condition. In the top-up strategy, a transportation agency contributes the full cost of a hydraulic design culvert for roads with a score of 4 or lower; the conservation group pays additional costs to upgrade to an AOP design (bottom panel). The conservation group pays the full cost of an AOP design project for roads with a score of 5 or higher. In a discounting strategy, the road agency contribution is inversely proportional to road surface condition, but would never exceed the cost of a hydraulic-design culvert.

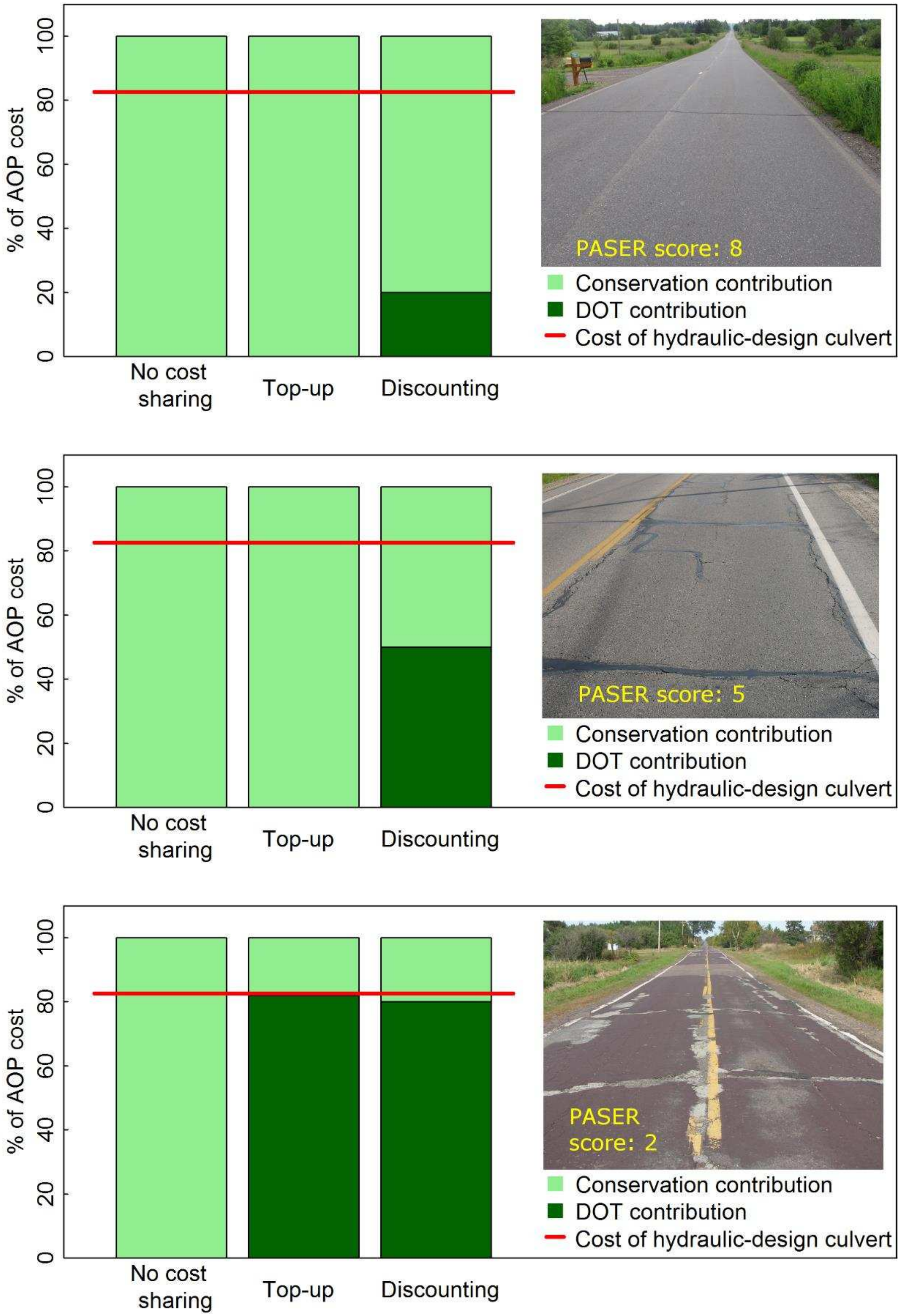
Figure 2: (A) Histogram of PASER scores across Michigan for 2004 (based on 164,506 surveyed road segments) and 2013 (121,624 surveyed road segments). In 2004, 10.5% of surveyed road segments received a score of 4 or lower; in 2013, that number rose to 36%. (B) Distribution of road crossings (both bridges and road culverts) across Strahler stream orders for all road crossings in Michigan, and for those with road surface condition 4 or lower.

Figure 3: (A) Return-on-investment curves for three cost-sharing strategies in the resident fish (DCI) optimization model. (B) The percentage increase in ROI that could be achieved for a budget of $30 M for all combinations for two cost-sharing strategies and three AOP culvert cost models (Linear, Compromise, BFW). (C) The distribution of all road crossings, and selected

projects under each cost-sharing strategy, across Strahler stream order for a budget of $30 M. (D) The number of projects in an optimal portfolio with a $30 M budget for each of the three cost-sharing strategies. In panels A, C and D, AOP culvert costs are calculated using the Linear cost model.

Figure 4: (A) Percentage increase in return-on-investment resulting from top-up cost-sharing for the resident fish (DCI) and Great Lakes migratory fish optimization models. (B) The proportion of optimal project portfolios represented by road culvert (RSX) projects when following a top-up cost-sharing strategy for the resident fish (DCI) and Great Lakes migratory fish optimization models.

Figure 1



% of AOP cost
0
20
40
60
80
100
No cost sharing
Top-up
Discounting
PASER score: 8
PASER score: 5
PASER score: 2
Conservation contribution
DOT contribution
Cost of hydraulic-design culvert

Figure 2

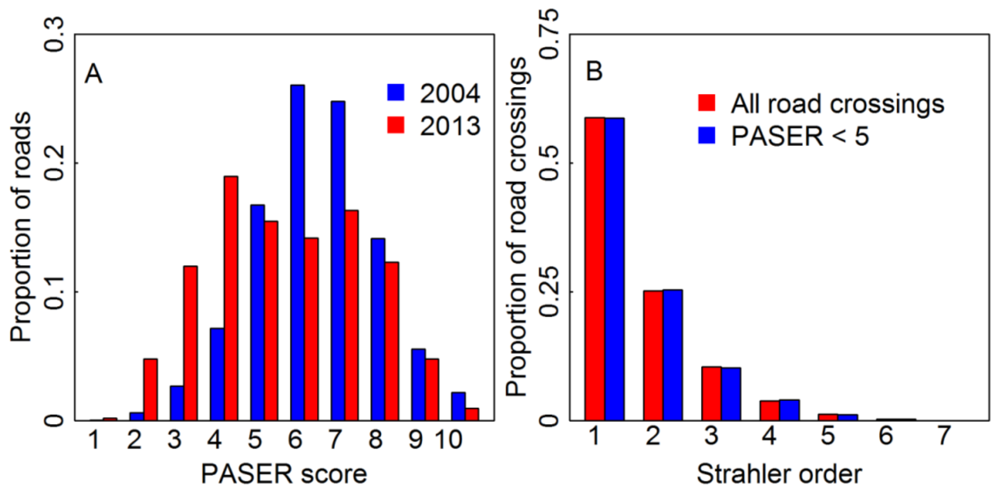

A
2004
2013
Proportion of roads
0
0.1
0.2
0.3
1 2 3 4 5 6 7 8 9 10
PASER score
B
All road crossings
PASER < 5
Proportion of road crossings
0
0.25
0.5
0.75
1 2 3 4 5 6 7
Strahler order

Figure 3

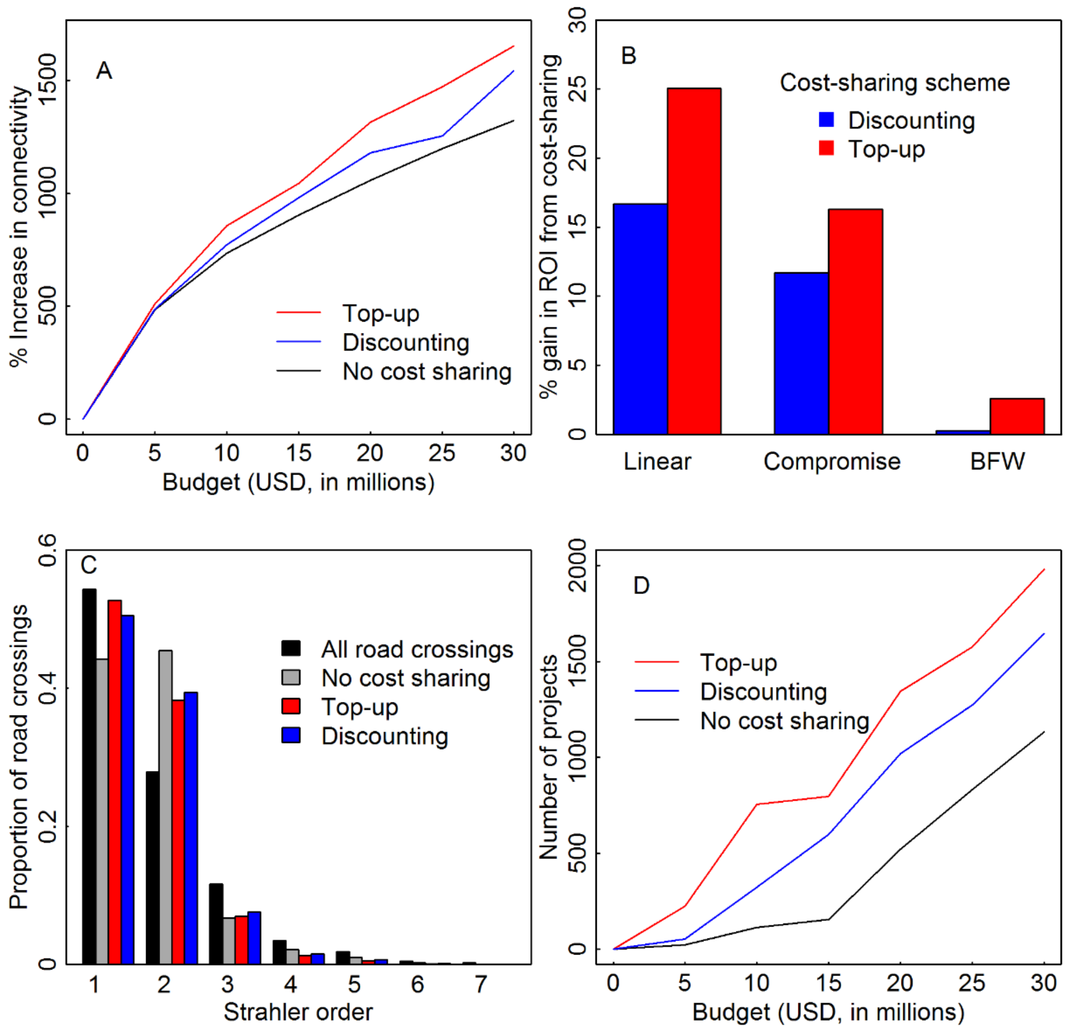
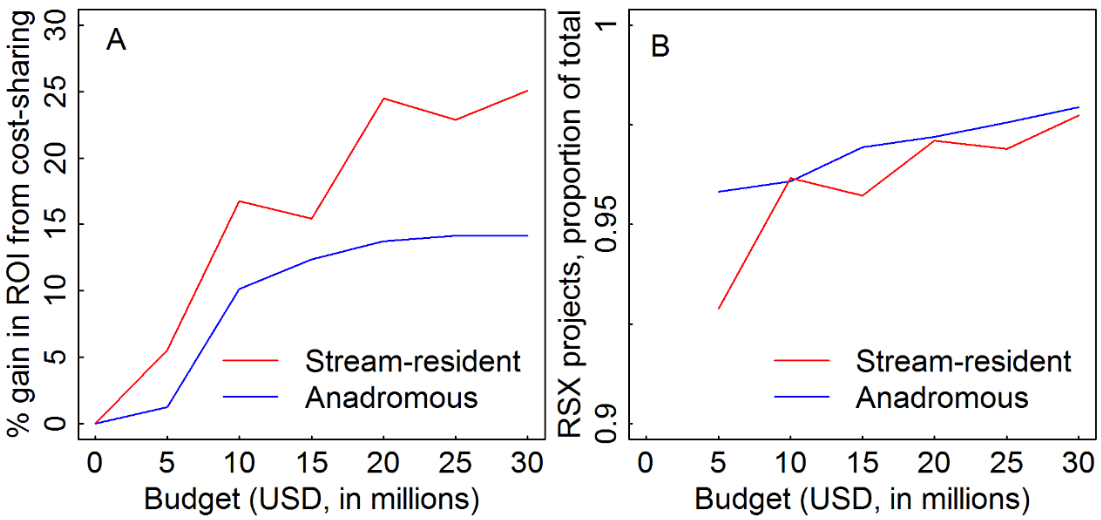

A
% Increase in connectivity
0
500
1000
1500
0
5
10
15
20
25
30
Budget (USD, in millions)
Top-up
Discounting
No cost sharing
B
% gain in ROI from cost-sharing
0
5
10
15
20
25
30
Cost-sharing scheme
Discounting
Top-up
Linear
Compromise
BFW
C
Proportion of road crossings
0
0.2
0.4
0.6
All road crossings
No cost sharing
Top-up
Discounting
1
2
3
4
5
6
7
Strahler order
D
Number of projects
0
500
1000
1500
2000
Top-up
Discounting
No cost sharing
0
5
10
15
20
25
30
Budget (USD, in millions)

Figure 4



A
% gain in ROI from cost-sharing
0
5
10
15
20
25
30
Budget (USD, in millions)
Stream-resident
Anadromous
B
RSX projects, proportion of total
0.9
0.95
1

Appendix A: State transition model of road decay over time

To estimate the 2013 PASER ratings of road segments that were last surveyed in an earlier year, we created a series of state transition matrices to describe how roads degrade over time. Changes in the PASER rating of a road segment over time are due to either further degradation of the road surface (decrease in PASER score) or resurfacing or repair (increase in PASER score). Of the 781,407 road segments in our data base, 725,728 segments were assessed at least twice during the years 2004 to 2013. We used these longitudinal observations of road surface condition to create a series of transition matrices (or Markov matrices) and calculate the expected condition of each road segment in 2013.

Changes in pavement condition over time generally follow a sigmoid or logistic curve (WDOT 2002). As a result, the expected pavement condition for a road segment last measured before 2013 depends on both the interval of time since it was last assessed, and the pavement condition at that assessment. Accordingly, we created a separate transition matrix for each interval of n years between assessments.

To estimate the PASER ratings of road segments last surveyed in year$2013 - n$, we first identified all road segments that were assessed at an interval of n years. We then used these longitudinal observations to create a transition matrix $\boldsymbol{P}$, where the element P_{ij}describes the probability that a road segment with PASER score i would transition to score j after an interval of n years. We then calculated the mean value of each row of this matrix and took this value to be the expected 2013 condition of a road segment that was assessed to have condition i in year$2013 - n$.

Appendix B: Formulation of a Model to Optimize River Connectivity for Stream-Resident Fish

The model that we propose for optimizing river infrastructure investments for stream-resident fish is based on the Dendritic Connectivity Index ($\mathrm{DCI_P}$) proposed by Cote et al. (2009). $\mathrm{DCI_P}$ provides a river network scale measure of habitat connectivity and is evaluated by taking a weighted average of the probability that fish can successfully travel between any two sections of a river. More formally, it is defined as:

$$\mathrm{DCI_P} = \frac{1}{V^2}\sum_{i\in S}\sum_{j\in S} v_i v_j \varphi_{ij} \quad \text{(A1)}$$

where S is the set of stream sections, indexed by i and j, φ_{ij} denotes the cumulative passability between stream sections i and j, v_i and v_j specify the size of stream sections i and j (normally measured in terms of length), and $V = \sum_i v_i$ gives the total size of the river network. Letting B_{ij}, indexed by k, represent the set of barriers lying between river sections i and j, cumulative passability is calculated simply as:

$$\varphi_{ij} = \prod_{k\in B_{ij}} p_k \quad \text{(A2)}$$

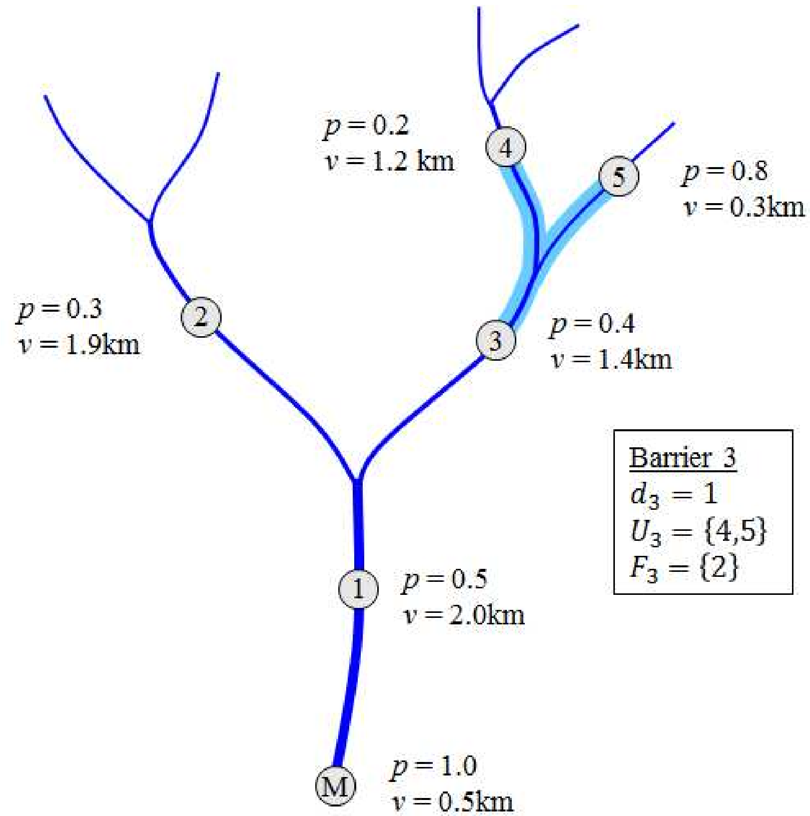
where p_k denotes the "bidirectional" passability of barrier k, which is taken as the product of barrier k's upstream and downstream passabilities p_k^{up} and p_k^{dwn} (i.e., $p_k = p_k^{up} \times p_k^{dwn}$). Barrier passability represents the fraction of fish (in the range 0 to 1) that are able to successfully negotiate a barrier in the upstream or downstream directions.

To formulate an optimization model that maximizes DCI$_P$ for one or more fish species across one or more watersheds, we first introduce the concept of a river "subnetwork." A river subnetwork corresponds to the area upstream of a barrier up to the next set of barriers or the river terminus. Assuming a river network is strictly dendritic (i.e., never diverges in the downstream direction), a subnetwork can be uniquely identified by its most downstream barrier, thereby making a barrier and a subnetwork entirely interchangeable terms. Figure A1 shows an example involving 6 barriers/subnetworks.

To continue, we let J denote the set of barriers within the river network, indexed by j and k. For each barrier j, the immediate downstream barrier is given by d_j, while U_j and F_j represent the set of barriers immediately upstream from j and the set of barriers that are directly confluent with j, respectively. An illustration of how d_j, U_j, and F_j are determined for a specific barrier is shown in Figure A1.

The set of fish species, guilds or taxa of restoration concern (a.k.a. "targets") is denoted by T and indexed by t. Associated with each target t is a weight $w_t \geq 0$ that specifies the importance of improving connectivity for t. With this in place, let v_{jt} specify the net amount of

Figure A1. An example barrier network. For each barrier, the current bidirectional passability p and the amount of river habitat v in the subnetwork immediately above the barrier are provided. The subnetwork specific to barrier 3 is highlighted in light blue. Barriers making up parameters/sets d_j, U_j, and F_j for barrier $j = 3$ are also provided. Note that barrier M is a dummy barrier located at the river mouth with initial passability 1 to ensure that all habitat within the river network is included in the calculation of the DCI$_P$ metric.



river habitat above barrier j (i.e., within subnetwork j) for target t, let $V_t = \sum_j v_{jt}$ be the total amount of habitat for target t within the study area, let $v_j = \sum_t w_t v_{jt}$ be the weighted amount of habitat in subnetwork j, and let $V = \sum_t w_t V_t$ be the total weighted amount of habitat within the system. For each target t, initial passability of barrier j is given by p_{jt}^0. Given mitigation (i.e., repair or removal) of barrier j at a cost of c_j, passability for target t increases by an amount p'_{jt}. It is assumed that a budget b is available for barrier mitigation.

Finally, we introduce the following decision variables.

$$x_j = \begin{cases} 1 & \text{if barrier } j \text{ is mitigated} \\ 0 & \text{otherwise} \end{cases}$$

z_j = total amount of weighted habitat accessible from subnetwork j

z_{jt}^{dwn} = amount of accessible habitat for target t within and downstream of subnetwork j

z_{jt}^{up} = amount of accessible habitat for target t upstream of barrier j

y_{jt}^{dwn} = increase in accessible habitat for target t downstream of subnetwork j

y_{jt}^{up} = increase in accessible habitat for target t upstream of barrier j

A mathematical formulation of our model is then given below.

$$\max \frac{1}{V^2} \sum_{j \in J} v_j z_j \tag{A3}$$

$s.t.$

$$\sum_{j \in J} c_j x_j \leq b \tag{A4}$$

$$z_j = \sum_{t \in T} w_t \left(z_{jt}^{dwn} + \sum_{k \in U_j} z_{kt}^{up} \right) \qquad \forall j \in J \tag{A5}$$

$$z_{jt}^{dwn} = p_{jt}^0 \left(z_{d_j t}^{dwn} + \sum_{k \in F_j} z_{kt}^{up} \right) + v_{jt} + y_{jt}^{dwn} \qquad \forall j \in J, t \in T \tag{A6}$$

$$y_{jt}^{dwn} \leq V_t x_j \qquad \forall j \in J, t \in T \tag{A7}$$

$$y_{jt}^{dwn} \leq p'_{jt} \left(z_{d_j t}^{dwn} + \sum_{k \in F_j} z_{kt}^{up} \right) \qquad \forall j \in J, t \in T \tag{A8}$$

$$z_{jt}^{up} = p_{jt}^0 \left(\sum_{k \in U_j} z_{kt}^{up} + v_{jt} \right) + y_{jt}^{up} \qquad \forall j \in J, t \in T \tag{A9}$$

$$y_{jt}^{up} \leq V_t x_j \qquad \forall j \in J, t \in T \tag{A10}$$

$$y_{jt}^{up} \leq p'_{jt}\left(\sum_{k\in U_j} z_{kt}^{up} + v_{jt}\right) \qquad \forall j \in J, t \in T \qquad \text{(A11)}$$

The objective (A3) maximizes total habitat availability within the study area. To understand the connection between (A1) and (A3), note that with only one target the amount of habitat accessible from subnetwork j is simply equal to $z_j = \sum_{i\in J} v_i \varphi_{ij}$. The objective function (A3) is then obtained through a simple rearrangement of the terms in (A1):

$$\frac{1}{V^2}\sum_{j\in J}\sum_{i\in J} v_i v_j \varphi_{ij} = \frac{1}{V^2}\sum_{j\in J} v_j \sum_{i\in J} v_i \varphi_{ij} = \frac{1}{V^2}\sum_{j\in J} v_j z_j$$

To continue, constraint (A4) specifies that the total cost of barrier mitigation cannot exceed the available budget b. Equations (A5) determine the total weighted amount of habitat z_j accessible from subnetwork j, which is calculated, for any given target t, by decomposing accessible habitat into "downstream" (z_{jt}^{dwn}) and "upstream" ($\sum_{k\in U_j} z_{kt}^{up}$) portions.

The amount of accessible habitat within and downstream of subnetwork j is determined by equations (A6). Looking at this equation in detail, the initial amount of habitat below subnetwork j is given by $p_{jt}^0\left(z_{d_jt}^{dwn} + \sum_{k\in F_j} z_{kt}^{up}\right)$, the sum of habitat immediately downstream form j ($z_{d_jt}^{dwn}$) and the habitat confluent with j ($\sum_{k\in F_j} z_{kt}^{up}$), multiplied by the initial passability of j (p_{jt}^0). Added to this is $v_{jt} + y_{jt}^{dwn}$, the amount of habitat within subnetwork j (v_{jt}) plus any increase in downstream accessible habitat (y_{jt}^{dwn}).

The increase in downstream accessible habitat y_{jt}^{dwn}, meanwhile, is determined by inequalities (A7) and (A8). Constraint (A7) specifies that if a barrier has not been mitigated ($x_j = 0$), then there can be no increase in downstream accessible habitat (i.e., $y_{jt}^{dwn} \leq 0$). If mitigation is carried out on barrier j, then (A7) is nonbinding and (A8) specifies that y_{jt}^{dwn} is bounded above by the amount of habitat strictly below j ($z_{d_jt}^{dwn} + \sum_{k \in F_j} z_{kt}^{up}$) multiplied by the change in passability at barrier j (p'_{jt}). Constraints (A9)-(A11) serve an analogous function as (A6)-(A8) for determining the amount of accessible habitat upstream of j).

It is important to point out that equations (A6) and (A9), as well as inequalities (A8) and (A11), are determined in a recursive manner and form a type of specialized network flow structure. Take (A6), for example. Downstream accessible habitat z_{jt}^{dwn} is determined in part by the amount of habitat downstream from j ($z_{d_jt}^{dwn}$) and in part by upstream habitat confluent with j ($\sum_{k \in F_j} z_{kt}^{up}$). The term z_{jt}^{dwn}, in turn, feeds into the calculation of downstream habitat for subnetworks upstream from j (i.e., z_{kt}^{dwn} such that $k \in U_j$ via term $z_{d_kt}^{dwn} = z_{jt}^{dwn}$).

This is the major novelty of our formulation, which is akin the "probability chain" concept introduced in O'Hanley et al. (2013) and subsequently applied to resident fish passage barrier mitigation in King (2017). The main difference from the approach adopted in King (2017) is that instead of calculating cumulative passability values (i.e., the φ_{ij} terms), we use a network flow structure to calculate downstream and upstream habitat availability (i.e., the z_{jt}^{dwn} and z_{jt}^{up} terms). The main advantage and novelty of newly proposed linearization is that it requires substantially fewer auxiliary variables and constraints, thus resulting in significantly reduced run times to solve the model.

Our proposed model was coded in OPL, the programming language tied to the IBM ILOG CPLEX Optimization Studio platform. OPL is a high-level algebraic modeling language for formulating linear optimization problems. The OPL implementation of our model was solved using the CPLEX mixed integer linear programming (MILP) solver.

Appendix C: Sensitivity Analysis

We performed a sensitivity analysis to quantify the degree to which model outputs might depend on uncertainty in the underlying data. For each of the three key parameters that influence optimization model outputs (project costs, barrier passability, and total length of river upstream of each barrier to the nearest set of upstream barriers), we performed an independent sensitivity test by randomly increasing or decreasing each value of that parameter in the data set by 10% while holding all other parameters constant. We repeated this process 15 times for each of the three key parameters, generating a total of 45 iterations of our data set. For each of these 45 data sets, we then calculated the percentage increase in connectivity (as measured by DCI) for stream-resident fish that could be achieved for budgets of $5 million and $20 million.

Overall, we found that optimization model outputs were relatively insensitive to variation in input parameters (Fig. C1, C2). For a budget of $5M, for example, the greatest variation in connectivity gains resulted from altering project costs (Fig. C1A); however, even in that case, randomly assigning project costs to be ± 10% of their estimated value resulted in only ± 2.5% in connectivity gains. For a budget of $5 M, increases in connectivity were less dependent on variability in passability estimates (Fig.C1B) and upstream river length (Fig. C1C). For a budget of $25 M, the greatest variation in connectivity gains resulted from altering estimates of upstream river length (Fig. C2C); in the case, randomly assigning estimates of upstream river length to be ± 10% of their estimated value resulted in ± 2.6% in connectivity gains. For a budget of $20 M, increases in connectivity were less dependent on variability in estimates of project costs (Fig. C2A) and barrier passability (Fig. C2B).

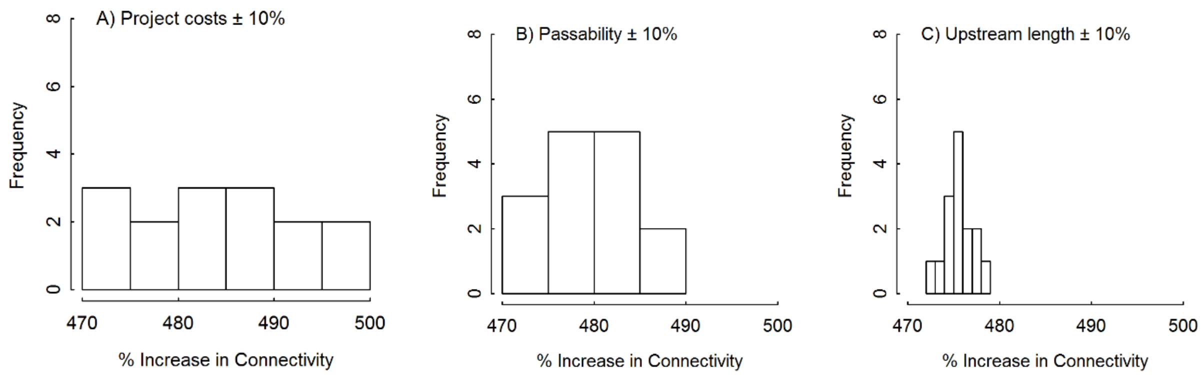


Figure C1: Variation in the percent increase in connectivity (as measured by DCI) that could be achieved for a budget of $5 million under three sensitivity tests: A) manipulating estimates of project costs to be ± 10% of their estimated value, B) manipulating passability estimates to be ± 10% of their estimated value, and C) manipulating estimates of upstream river length to be ± 10% of their estimated value.

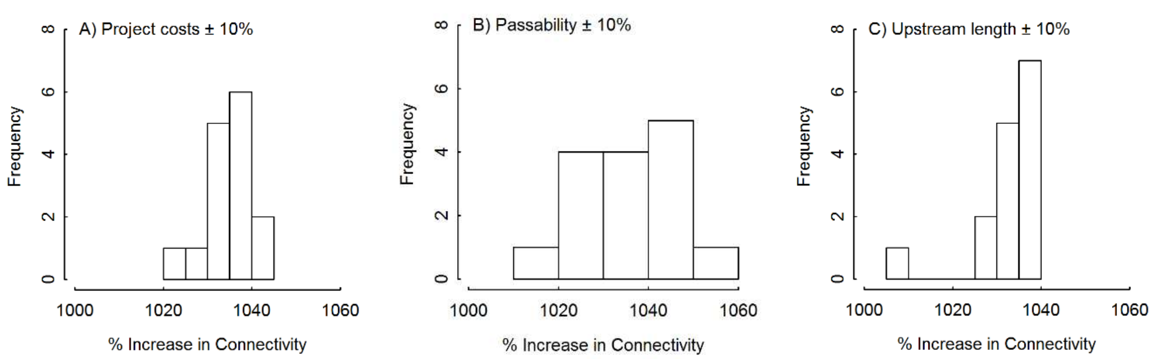


Figure C2: Variation in the percent increase in connectivity (as measured by DCI) that could be achieved for a budget of $20 million under three sensitivity tests: A) manipulating estimates of project costs to be ± 10% of their estimated value, B) manipulating passability estimates to be ± 10% of their estimated value, and C) manipulating estimates of upstream river length to be ± 10% of their estimated value.