**Fish Passage Barrier Removal Board – Meeting Notes**
**Date: April 24, 2015**
**Place: Governor Hotel, Olympia, Washington**

**Summary: Agenda items with formal action**

| Item | Formal Action |
|---|---|
| Meeting Notes | Approved meeting notes from March 20 |

**Summary: Follow-up actions**

| Item | Follow-up |
|---|---|
| Request to LEs to prioritize HUC 10s | Julie will send draft to FBRB members for comment and then send to LEs |
| Draft Workplan | Neil will contact individual members of FBRB and prepare a final draft for review at next meeting |

**Board Members/Alternates Present/on the phone:**

| | |
|---|---|
| David Price, Chair, WDFW | Donelle Mahan, WDNR |
| Julie Henning, WDFW | Brian Abbott, GSRO |
| Paul Wagner, DOT | Carl Schroeder, AWC |
| Jonalee Squeochs, Yakama Tribe | |

**Welcome/Introductions/Agenda Review**
The meeting was called to order at 9:30 a.m. by facilitator Neil Aaland. Neil reviewed the agenda for the day. He then asked Board members and attendees to introduce themselves. A motion was made by David Price to approve the September meeting notes; Paul Wagner seconded. The motion passed unanimously.

**Public Comments:** No one present offered comments.

**Updates on legislative session**
Julie attended a watershed leads council meeting with Puget Sound Lead Entities (LEs). She gave a presentation on the Fish Passage Barrier Removal Board, provided information on the intent of the statue, and gave some information on board progress in developing a barrier removal strategy. One specific question she asked the LEs is if they could nominate a watershed they thought could have the largest contribution to salmon recovery if fish barriers were removed. They said they believed they could do that. The next step is for the FBRB to provide more direction and a process for them to use in Puget Sound. The FBRB needs to consider how to address a situation where the LEs propose multiple watersheds.

**Updates on Legislative Session**
Carl Schroeder said they have been working on funding, and there is some in bill 5997. It's in the same form as discussed at the last meeting. The bill is in House Rules.

Dave Price and several other FBRB members made a presentation to the House Agriculture and Natural Resources committee. The presentation was well received. Committee members seemed surprised at the number of barriers.

**Developments on the Statewide Strategy**
There are three components of this agenda item. The first one is reviewing the size of a HUC 10 with a Puget Sound focus. There is still some confusion about what a HUC 10 includes. Justin Zweifel from WDFW presented some slides and discussed this topic. He showed a slide of Puget Sound HUC 10s,

overlaid with Lead Entity boundaries. There are 120 HUC 10s within the Puget Sound Recovery Region, including Hood Canal.

Questions and comments included:

- The maps of Puget Sound HUC 10s are available from USGS as a shape file
- The maps don't reflect forest service barriers
- Green dots on the map show pass able streams, red dots have barriers

The next component for discussion is the proposed Puget Sound criteria for selecting HUC 10s, which is the main part of this agenda item. WDFW needs to get comments and approval from the FBRB so it can begin working with Lead Entities. One potential criteria is escapement. The relevant of escapement is low numbers could mean there is not a lot of potential for that stream; but it could also mean barriers should be removed. The numbers can tell you if there's a population and how healthy it is. There are limitations to this, the lack of data collected. It's of limited value for scoring criteria but might be of use in allowing entities to choose high priority watersheds in individual project areas.

Cade Roler took over the presentation and this point. He discussed proposed criteria 1 – Intrinsic Potential (IP) model. He reviewed how WDFW has used the model, and showed as an example the Lower Nooksack River. The information for the IP model is available statewide. This doesn't take into account known barriers; that information gets added after HUC 10s are chosen. Some concern was raised that we need to know this before the selection; Julie said we need to get to the HUV 10 level before we can add this kind of information. Cade explained how the percentages were calculated.

Questions and comments:

- This seems like a reasonable first cut
- The Board might be more interested in the habitat amount than in the percentage; the absolute mounts
- Don't want to disadvantage the large HUC 10s
- Some discussion around not picking focus areas, but putting the strategy on specific sites
  - The Legislature told the FBRB to develop a strategy
  - Carl mentioned the proviso funding is predicated on having the Board help direct funding to appropriate areas
  - Paul is concerned about over-thinking a "grand scheme"
  - Need to be both strategic and opportunistic
- Julie thinks we should circle back to this next month; they'll send out information to LEs providing guidance

Criteria 2: "Shovel ready." Get some sense of how many projects within a HUC 10 have been scope. This presumes all HUCs may have this information available.

Criteria 3: temperature. Dave wondered if this should be a factor, since not a lot of distinction here. Donelle thought there's a little bit of value. Cade suggested this would not be used as a standalone; it's a coarse-scale item used in conjunction with other information.

Criteria 4: Limited impervious surfaces. Some concern from a city's standpoint; most impervious surfaces are in cities. Just be sure having impervious surfaces doesn't exclude too much. Paul thinks at the HUV level probably want more work in lower levels of impervious surfaces; helps inform the whole picture. Dave thought this factor should only be considered when comparing between HUC 10s.

Criteria 5: Steelhead spawning habitat. Idea is to supplement the IP model; this is based on mapped streams. Cade said he would overlay this information on IP and see where they match. FBRB members thought this would be food information.

Criteria 6: Healthy riparian habitat. This is time-intensive, involving fieldwork. It took a week to do this in WRIA 1. It probably would not take as long for others. Would do this on the nominated HUC 10s, not on all. Comments and questions:

- Buffer distance of 150 meters can be adjusted
- Could be a surrogate for temperature and other attributes of stream health
- Could consider doing land use; would pull away from cities
- Areas further up the watershed would score higher
- Dave thought this could overlap with temperature and impervious surface
- This helps inform those criteria
- Perhaps ask for an estimate from Les – a qualitative narrative
- Is there a coarser scale, such as looking at and use designations?

Conclusions for this discussion: WDFW can move forward with the request to Les to nominate HC 10s. Need to think about the "auxiliary on-ramp", AKA the opportunistic projects. WDFW will send a draft around before sending this to Les.

The meeting adjourned at noon – several people could not come back after lunch and the group would no longer have a quorum.

**The next meeting of the Board is scheduled for XXX**

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**Others present at meeting:**

| | |
|---|---|
| Neil Aaland, Facilitator | Justin Zweifel, WDFW |
| Cade Roler, WDFW | Larry Dominguez, WDFW |
| Colleen Thompson, RFEG Coalition | |

# Fish Barrier Removal Board
# *Draft Work Plan*

In 2014, the Washington State Legislature created the Fish Passage Barrier Removal Board to develop a coordinated barrier removal strategy and provide the framework for a fish barrier grant program. The board is established by Chapter 77.95 RCW.

## Mission

.The duty of the board is to identify and expedite the removal of human-made or caused impediments to anadromous fish passage in the most efficient manner practical through the development of a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers caused by state and local roads and highways and barriers owned by private parties.[1]

## Values

The board values all aspects of salmon recovery and the existing structure developed under the 1999 Salmon Recovery Act, and provides a statewide fish barrier removal strategy and program funding recommendations to the legislature. The board will ensure that the processes to identify, prioritize and fund projects are based on maximizing the opening of high quality habitat through a coordinated investment strategy that prioritizes projects necessary to eliminate fish barriers owned by state and local government, tribes, private parties, and others. This investment strategy values (1) opening high quality salmon habitat that can contribute to salmonid recovery, (2) coordinating with others doing barrier removals to achieve the greatest cost savings, and (3) correcting barriers located furthest downstream.

To achieve the mission, goals, and values the Board will:

- Improve coordination of existing fish passage programs to increase the benefits of barrier removal among multiple jurisdictions.
- Expedite the removal of barriers in the most efficient manner practical through economy of scale and streamline permitting processes.
- Facilitate collaboration, coordination, and communication among state, federal and local agencies, tribes, regional salmon recovery organizations, salmon recovery lead entities, regional fisheries enhancement groups, conservation districts, restoration contractors, landowners and other interested stakeholders on fish passage improvement programs and projects.
- Expedite implementation of on-the-ground projects by identifying and addressing institutional hurdles.
- Educate and increase the public and agency awareness of fish passage issues to develop support for solving problems and preventing new ones.
- Seek funding sources for fish passage projects within Washington and administer a strategic funding program to further the Board's mission once funding is secured.

## Goals & Actions

The board provides support to local fish passage programs based on its priorities, available resources, and

[1] RCW 77.95.160 (2) (a)

emergent opportunities.

**Goal 1: The Washington Department of Fish & Wildlife shall chair and administer a Fish Passage Barrier Removal Board (FBRB).**

A. *Action*: The WDFW will organize, chair, and provide staff support for the Fish Barrier Removal Board.[2]

   *Responsible Party/Timeline*: WDFW/Ongoing

B. *Action:* Internal communication: Create clear communication to describe board role and duties. Some of this has already been accomplished, including Board by-laws and meeting notes. Additional items to develop include a communication strategy, work plan, fact sheet, and webpage.

   *Responsible Party/Timeline*: FBRB/By August 2015

C. *Action:* External communication: Develop a communication strategy, using an outside communication specialist. See Goal 5 for more information on this action.

   *Responsible Party/Timeline*: FBRB/By August 2015

D. *Action:* The Board should review, on an annual basis, the current membership of the FBRB and consider adding members as appropriate.

   *Responsible Party/Timeline*: Chair and FBRB/annually beginning June 2015

E. *Action:* The Board will develop and implement an annual work plan.

   *Responsible Party/Timeline*: FBRB/By June 2015 with annual updates

**Goal 2: Develop a Communication Strategy**

A. *Action*: The Board will identify communication strategy elements and timeframes for implementing them. Elements may include developing key messages; identifying target audiences for each type of messaging; coordinating with other fish barrier removal programs; deciding how to share information developed by this Board; connecting with other entities including the federal government, tribes, and railroads; and deciding on an education and information strategy. Low cost early activities should also be considered and included in the strategy. The strategy should be reviewed annually by the Board.

   *Responsible Party/Timeline*: WDFW, with assistance from an outside communications expert and other FBRB members/Complete by September 2015 and begin implementing at that point

B. *Action:* The Board will participate in the May 2015 Salmon Recovery Conference being held in Vancouver, Washington. There is a specific slot addressing fish passage, and a number of key players

[2] RCW 77.95.160 (1): "The board must be composed of a representative from the department, the department of transportation, cities, counties, the governor's salmon recovery office, tribal governments, and the department of natural resources. The representative of the department must serve as chair of the board and may expand the membership of the board to representatives of other governments, stakeholders, and interested entities."

involved in fish passage barrier removal projects will be present. The work of the Board can be shared with others interested in the same issues, and opportunities to coordinate and share information can be pursued. If time allows, key messages for sharing with participants should be identified by the FBRB.

*Timeline/Responsible Party*: May 2015/Chair, other members of the FBRB

C. *Action:* WDFW will prepare a report to the legislature by October 31, 2016 *[NOTE: Neil could not find a reference to this in enabling legislation; is this a requirement that exists elsewhere, such as in a proviso, or is it something that WDFW thinks needs to happen?]*. WDFW will also respond to requests from legislative committees and staff for information and briefings, with assistance from other FBRB members.

   *Responsible Party/Timeline:* WDFW and other FBRB members as requested/: October 31, 2016

D. *Action:* Connect with the Washington Forest Protection Association for outreach and to clarify efforts to coordinate with the barrier removal projects of their members.

   *Responsible Party/Timeline*: WDFW/Connect with WFPA by August 2015

E. *Action:* Meet with the Northwest Fisheries Commission and Columbia River Inter-Tribal Fisheries Commission to update them on the activities of the FBRB, obtain input on these activities, and assess their interest in coordinating the fish passage barrier removal programs of member Tribes.

   *Responsible Party/Timeline*: WDFW/Connect with WFPA by August 2015

**Goal 3: The FBRB will develop a coordinated approach to identifying and expediting the removal of fish passage barriers. As noted in the enabling legislation, "The duty of the board is to identify and expedite the removal of human-made or caused impediments to anadromous fish passage in the most efficient manner practical through the development of a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers caused by state and local roads and highways and barriers owned by private parties.[3]" The approach should reflect opportunities that exist within existing funding and programs as well as opportunities that will be provided by a future grant program.**

A. *Action:* Develop a statewide coordinated approach. Sub-actions needed to accomplish this action are listed in the table below:

***FBRB Members: Discuss what, in addition to the prioritization methodology, constitutes a strategy – prioritization is only one piece of an overall strategy. This table lists actions in addition to the prioritization that would constitute a strategy. Is an overall strategy reflected in this workplan? What pieces of the work plan are the strategy? How do we address what actions should occur apart from a grant program?***

[3] RCW 77.95.160 (2) (a) "The duty of the board is to identify and expedite the removal of human-made or caused impediments to anadromous fish passage in the most efficient manner practical through the development of a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers caused by state and local roads and highways and barriers owned by private parties."

| Sub-action | By Whom | Timeline |
|---|---|---|
| 1. Meet with on-the-ground implementers of barrier removal projects to gain an understanding of their perspectives on a strategy. This should include, at a minimum, Regional Fisheries Enhancement Groups (RFEGs), Conservation Districts (CDs), and the Associated General Contractors organization. Meetings can occur either as part of the agenda for FBRB meetings or by attending meetings of implementers, as appropriate. One opportunity is the upcoming Salmon Recovery Conference in May, 2015. | FBRB | Start during spring/summer 2015 |
| 2. Develop a prioritization methodology aimed at prioritizing which focus areas should be addressed first. Once those area are chosen then conduct strategic barrier inventories and develop prioritized lists of barriers. Work within the framework provided by the regional salmon recovery organizations and continue to work with them on the methodology. | FBRB | Summer 2015 |
| 3. Continue to work with the Puget Sound Partnership Salmon Recovery Council (SRC) to define a Puget Sound approach. Initial discussions have already occurred with the SRC, and work will continue as needed to incorporate into the overall FBRB prioritization approach. | WDFW | Summer 2015 |
| 4. Get feedback from the public on the draft prioritization methodology; consider comments and adopt a final prioritization methodology. | FBRB | Summer 2015 |
| 5. WDFW was not given any additional resources to support the Fish Barrier Removal Board. Although some existing resources are available, additional resources are needed to support the development of the Fish Barrier Removal Board statewide strategy, prioritization methodology, and development of grant program framework. WDFW will first do an assessment of what resources are needed to implement this work plan and present this to the FBRB. Second, WDFW and the FBRB will seek out these additional resources. | WDFW for assessment; all FBRB members for locating resources | Assessment due December 2015, search for resources ongoing after that |
| 6. Develop a plan to coordinate information sharing and coordination between the FBRB and other entities involved in fish passage barrier removal projects. The plan should address how the FBRB will coordinate with other state and federal programs on project funding lists; how communication and outreach will work; and how the information already known can be shared. | FBRB | By December 2015, with annual updates |
| 7. The FBRB will discuss technical assistance through the program and how it will be provided. This is referenced in RCW 77.95.170 (5) (b). Determine the scope of technical assistance that WDFW needs to provide, including barrier inventory training and other training/technical assistance needed. Develop the “technical assistance toolbox” that WDFW will offer. | WDFW with FBRB assistance | By December 2015 |

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|---|---|---|
| 8. The authorizing legislation provides that WSDOT and WDFW will coordinate to ensure that fish passage barrier removal programs are synchronized. [4][i]WDFW and WSDOT will report annually to the FBRB on the status of their joint efforts. It is not intended that the FBRB has any oversight, but rather this information will inform the work of the FBRB. | WDFW and WSDOT | First report September 2015; annually thereafter |
| 9. Develop recommendations to the legislature, as part of a periodic report. Recommendations will be by WRIA with assistance from the regional salmon recovery organizations. | FBRB | Biennially |
| 10. Develop a funding package for a potential grant program (see goal 5). | FBRB | Summer 2016 |

**Goal 4: WDFW Fish Passage Database**

A. *Action:* The FBRB receives a database management update. This will include a general briefing from WDFW and a demonstration of the database.

   *Responsible Party/Timeline* WDFW/September 2015

B. *Action:* The FBRB receives a briefing on WDFW's training program as described by the enabling legislation. The purpose of the training is to increase the awareness and consistency of fish passage barrier data collection, use of WDFW's database, and modern techniques of fish passage barrier correction methods.

   *Responsible Party/Timeline*: WDFW/By December 2015

C. *Action*: The authorizing legislation[5] reference to a "centralized database directory." It is unclear what is mean by this reference and it should be clarified.

   *Responsible Party/Timeline*: WDFW/By December 2015

D. Retrieve RMAP data from DNR annually to maximize opportunities for coordinated projects and grant project pathways

   *Responsible Party/Timeline:* WDFW/retrieve RMAP information annually (is there a logical time for this to occur - particular time when RMAP data has been refreshed?)

**Goal 5: Grant Program**

A. *Action*: Identify available and funding that could be used for the program and a proposed funding mechanism.

   *Responsible Party/Timeline*: WDFW (with assistance from other FBRB members)/ By December 2015



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[4] RCW 77.95.180 (1) (b)

[5] RCW 77.95.170 (5) (a): "The department shall establish a centralized database directory of all fish passage barrier information. The database directory must include, but is not limited to, existing fish passage inventories, fish passage projects, grant program applications, and other databases. These data must be used to coordinate and assist in habitat recovery and project mitigation projects."

B. *Action*: Develop a grant program that will allocate available funding, and address elements including match requirements, whether and how funding might be allocated between regions, provisions for opportunities that emerge ("just-in-time" or "shovel-ready" projects) and other factors. Continue developing the "hybrid option #3" discussed at the February 2015 meeting of the FBRB.

*Responsible Party/Timeline*: FBRB/By December 2015

**Goal 6: Project Permitting and Streamlining**

A. Action: Seek permitting efficiencies and streamlining regarding federal permits. Coordinating with the Governor's office, initiates contact with USACE, NOAA, and USFWS to explore and develop the feasibility of bundling of projects under any available nationwide permits for the purpose of achieving streamlined federal permitting.

*Responsible Party/Timeline*: WDFW/ By XXXX 2015

B. *Action:* Seek permitting efficiencies and streamlining regarding local and state permits. Work with local government planners to seek efficiencies and streamlining regarding shoreline permits, critical areas permits, and HPAs; and other actions as needed.

*Responsible Party/Timeline*: ?/By XXXX 2015

**TIMELINE FOR ACTIONS**

[**List action items in chronological order for easy reference – will be filled out when FBRB adopts a final workplan]**

| ACTION | TIMELINE | RESPONSIBILITY |
|---|---|---|
| Establish Fish Passage Barrier Removal Board | 6/2014 | WDFW |
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# Request to Puget Sound Lead Entity Organizations on watersheds to correct fish barriers:

## Information needed on where to start restoring ecosystem connectivity

**June 1, 2015**

**Background**

In 2014, legislation passed directing the creation of the Fish Barrier Removal Board (FBRB). The FBRB is tasked with developing a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers for anadromous salmonids caused by state and local roads, highways, and barriers owned by private parties across the state. The intent of the new law is to maximize anadromous fish access to high quality habitat through a coordinated strategy that prioritizes opportunities to correct fish barriers (single or multiple) across a watershed, including the barriers located furthest downstream. While many fish passage investments have already been completed, thousands of barriers still remain.

The duty of the FBRB is to identify and expedite the removal of human-made or human-caused impediments to anadromous fish passage through the development of a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers. The coordinated approach must address all areas of the state with anadromous species.

The FBRB will develop recommendations by proposing funding mechanisms and methodologies to coordinate state, tribal, local, and volunteer barrier removal efforts across the state. The FBRB understands and has discussed the need for a program that includes watershed barrier inventories, landowner outreach, feasibility and design, and construction funding.

To develop a systematic approach to optimize barrier removals, the FBRB is interested in utilizing the state's existing salmon recovery framework developed under the 1999 Statewide Strategy to Recover Salmon and coordinating with existing salmon recovery programs. This effort is not an attempt to reshuffle existing resources but to create new funding sources to address fish passage issues throughout the state. The goal is to provide a net gain in resources available to complete fish passage work. The FBRB would like local input in the development of a statewide fish passage program with a regional framework. The FBRB needs regional assistance on where to begin in Puget Sound.

The WDFW is available to work directly with lead entities to share existing barrier information from the fish passage database if this would be helpful.

**Request to Lead Entities**

The FBRB is requesting lead entity input for developing a strategy for correcting fish barriers in anadromous streams (salmon, steelhead, other species). The FBRB is requesting that each lead entity provide the FBRB feedback on areas within your coverage (at the HUC 10 level, see USGS link to Hydrologic Units: https://water.usgs.gov/GIS/huc.html) where fish passage projects would have the largest benefit for salmon recovery and open high quality habitat. HUC 10s should benefit depressed, threatened, and endangered stocks or support tribal treaty rights. The HUC 10s used by a healthy or undefined stock status should be considered if high quality habitat can be made accessible with barrier removals that would result in increased salmon/steelhead production.

We would like your input on what <u>HUC 10s to focus on first, not individual barriers</u>. These prioritized watersheds will help the FBRB determine how to get the most value out of future project investments. <u>We request that each lead entity provide their high priority HUC 10</u>. Please include a paragraph on why you have selected the HUC10 and feel it is a good candidate for fish passage restoration.

The nominations will be reviewed by the FBRB and evaluated based on the following criteria:

- Steelhead and Coho salmon rearing habitat within the HUC 10
- Steelhead spawning habitat within the HUC 10
- Impervious surfaces within the entire watershed
- Water temperature, as identified by Ecology's 305 B listing, within the entire watershed

The FBRB will consider <u>additional factors</u> presented by the Lead Entities in support of their nomination. Please remember that this input is at a HUC 10 scale. We intend to have future discussions on individual streams and barriers, once HUC 10s are determined.

Please nominate one HUC 10 by June 30, 2015 and provide a brief justification of your nomination.

## Useful links:

FBRB Homepage: http://wdfw.wa.gov/about/advisory/fbrb/

USGS link to Hydrologic Units: https://water.usgs.gov/GIS/huc.html

SalmonScape: http://apps.wdfw.wa.gov/salmonscape/

Department of Ecology Water Quality Interactive Map: http://www.ecy.wa.gov/programs/wq/303d/index.html

# Additional information

Once the focus HUC 10s are chosen, the FBRB will be developing specific criteria to help guide project proposals that can be submitted by project proponents.  The FBRB does not currently have dedicated funding, but we anticipate funding through legislative action in the future once we have developed a prioritization framework. Focus HUC 10s will be a starting point to correct fish barriers with the understanding that after barriers are removed in the selected HUC 10s, additional areas will be identified.

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**Other considerations for determining HUC 10s for fish passage:**

- What critical anadromous populations would most benefit from fish passage projects within your region?
- If the barriers were fixed, which areas would have the highest contribution towards salmon recovery?
- Consider the Viable Salmon Population criteria:
    - Are the parent populations classified as "primary" or otherwise considered essential to recovery of the ESU?
    - To what extent would the restored watershed contribute to achieving viable salmonid population(s), relative to other populations?
    - Spatial structure - Does the watershed have potential to be a major or minor spawning area? Would it contribute a meaningful area for expanded distribution and reduced population risk due to increased spatial structure?
    - Abundance - Will the barrier restoration add a meaningful quantity of habitat to the population and to what extent might it contribute to improvements in abundance? Quantify the relationship of the fish potential in the restored watershed to the whole population (e.g., stream area, intrinsic potential, EDT or other life cycle model outputs).
    - Productivity - Is the quality of the habitat in the restored watershed worse than, similar to, or better than the quality of habitat in the rest of the population?
    - Diversity - Will the expanded distribution result in reduced risk for diversity? (e.g., unique habitat types, ecoregions, flow or temperature regimes that allow unique life history pathways to be successful).

The following pages include the three RCW's that govern the Fish Barrier Removal FBRB.

## RCW 77.95.160

# Fish passage barrier removal FBRB — Membership — Duties.

(1) The department shall maintain a fish passage barrier removal FBRB. The FBRB must be composed of a representative from the department, the department of transportation, cities,

counties, the governor's salmon recovery office, tribal governments, and the department of natural resources. The representative of the department must serve as chair of the FBRB and may expand the membership of the FBRB to representatives of other governments, stakeholders, and interested entities.

(2)(a) The duty of the FBRB is to identify and expedite the removal of human-made or caused impediments to anadromous fish passage in the most efficient manner practical through the development of a coordinated approach and schedule that identifies and prioritizes the projects necessary to eliminate fish passage barriers caused by state and local roads and highways and barriers owned by private parties.

(b) The coordinated approach must address fish passage barrier removals in all areas of the state in a manner that is consistent with a recognition that scheduling and prioritization is necessary.

(c) The FBRB must coordinate and mutually share information, when appropriate, with:

(i) Other fish passage correction programs, including local salmon recovery plan implementation efforts through the governor's salmon recovery office;

(ii) The applicable conservation districts when developing schedules and priorities within set geographic areas or counties; and

(iii) The recreation and conservation office to ensure that barrier removal methodologies are consistent with, and maximizing the value of, other salmon recovery efforts and habitat improvements that are not primarily based on the removal of barriers.

(d) Recommendations must include proposed funding mechanisms and other necessary mechanisms and methodologies to coordinate state, tribal, local, and volunteer barrier removal efforts within each water resource inventory area and satisfy the principles of RCW 77.95.180. To the degree practicable, the FBRB must utilize the database created in RCW 77.95.170 and information on fish barriers developed by conservation districts to guide methodology development. The FBRB may consider recommendations by interested entities from the private sector and regional fisheries enhancement groups.

(e) When developing a prioritization methodology under this section, the FBRB shall consider:

(i) Projects benefiting depressed, threatened, and endangered stocks;

(ii) Projects providing access to available and high quality spawning and rearing habitat;

(iii) Correcting the lowest barriers within the stream first;

(iv) Whether an existing culvert is a full or partial barrier;

(v) Projects that are coordinated with other adjacent barrier removal projects; and

(vi) Projects that address replacement of infrastructure associated with flooding, erosion, or other environmental damage. (f) The FBRB may not make decisions on fish passage standards or categorize as impassible culverts or other infrastructure developments that have been deemed passable by the department.

[2014 c 120 § 4; 2000 c 107 § 110; 1997 c 389 § 6; 1995 c 367 § 2. Formerly RCW 75.50.160.]

Notes:

**Findings -- 1997 c 389:** See note following RCW 77.95.100.

**Severability -- Effective date -- 1995 c 367:** See notes following RCW 77.95.150.

RCW 77.95.170

# Salmonid fish passage — Removing impediments — Grant program — Administration — Database directory.



(1) The department may coordinate with the recreation and conservation office in the administration of all state grant programs specifically designed to assist state agencies, private landowners, tribes, organizations, and volunteer groups in identifying and removing impediments to salmonid fish passage. The transportation improvement FBRB may administer all grant programs specifically designed to assist cities, counties, and other units of local governments with fish passage barrier corrections associated with transportation projects. All grant programs must be administered and be consistent with the following:

(a) Salmonid-related corrective projects, inventory, assessment, and prioritization efforts;

(b) Salmonid projects subject to a competitive application process; and

(c) A minimum dollar match rate that is consistent with the funding authority's criteria. If no funding match is specified, a match amount of at least twenty-five percent per project is required. For local, private, and volunteer projects, in-kind contributions may be counted toward the match requirement.

(2) Priority shall be given to projects that match the principles provided in RCW 77.95.180.

(3) All projects subject to this section shall be reviewed and approved by the fish passage barrier removal FBRB created in RCW 77.95.160 or an alternative oversight committee designated by the state legislature.

(4) Other agencies that administer natural resource-based grant programs shall use fish passage selection criteria that are consistent with this section when those programs are addressing fish passage barrier removal projects.

(5)(a) The department shall establish a centralized database directory of all fish passage barrier information. The database directory must include, but is not limited to, existing fish passage inventories, fish passage projects, grant program applications, and other databases. These data must be used to coordinate and assist in habitat recovery and project mitigation projects.

(b) The department must develop a barrier inventory training program that qualifies participants to perform barrier inventories and develop data that enhance the centralized database. The department may decide the qualifications for participation. However, employees and volunteers of conservation districts and regional salmon recovery groups must be given priority consideration.

[2014 c 120 § 3; 1999 c 242 § 4; 1998 c 249 § 16. Formerly RCW 75.50.165.]

## Notes:

**Findings -- Purpose -- Report -- Effective date -- 1998 c 249:** See notes following RCW 77.55.181.

## RCW 77.95.180

# Fish passage barrier removal program.

(1)(a) To maximize available state resources, the department and the department of transportation must work in partnership to identify and complete projects to eliminate fish passage barriers caused by state roads and highways.

(b) The partnership between the department and the department of transportation must be based on the principle of maximizing habitat recovery through a coordinated investment strategy that, to the maximum extent practical and allowable, prioritizes opportunities: To correct multiple fish barriers in whole streams rather than through individual, isolated projects; to coordinate with other entities sponsoring barrier removals, such as regional fisheries enhancement groups incorporated under this chapter, in a manner that achieves the greatest cost savings to all parties; and to correct barriers located furthest downstream in a stream system. Examples of this principle include:

(i) Coordinating with all relevant state agencies and local governments to maximize the habitat recovery value of the investments made by the state to correct fish passage barriers;

(ii) Maximizing the habitat recovery value of investments made by public and private forest landowners through the road maintenance and abandonment planning process outlined in the forest practices rules, as that term is defined in RCW 76.09.020;

(iii) Recognizing that many of the barriers owned by the state are located in the same stream systems as barriers that are owned by cities and counties with limited financial resources for correction and that state-local partnership opportunities should be sought to address these barriers; and

(iv) Recognizing the need to continue investments in the family forest fish passage program created pursuant to RCW 76.13.150 and other efforts to address fish passage barriers owned by private parties that are in the same stream systems as barriers owned by public entities.

(2) The department shall also provide engineering and other technical services to assist

nonstate barrier owners with fish passage barrier removal projects, provided that the barrier removal projects have been identified as a priority by the department and the department has received an appropriation to continue that component of a fish barrier removal program.

(3) Nothing in this section is intended to:

(a) Alter the process and prioritization methods used in the implementation of the forest practices rules, as that term is defined in RCW 76.09.020, or the family forest fish passage program, created pursuant to RCW 76.13.150, that provides public cost assistance to small forest landowners associated with the road maintenance and abandonment processes; or

(b) Prohibit or delay fish barrier projects undertaken by the department of transportation or another state agency that are a component of an overall transportation improvement project or that are being undertaken as a direct result of state law, federal law, or a court order. However, the department of transportation or another state agency is required to work in partnership with the fish passage barrier removal FBRB created in RCW 77.95.160 to ensure that the scheduling, staging, and implementation of these projects are, to [the] maximum extent practicable, consistent with the coordinated and prioritized approach adopted by the fish passage barrier removal FBRB.

[2014 c 120 § 2; 2010 1st sp.s. c 7 § 83; 1995 c 367 § 3. Formerly RCW 75.50.170.]

## Notes:

**Effective date -- 2010 1st sp.s. c 26; 2010 1st sp.s. c 7:** See note following RCW 43.03.027.

**Severability -- Effective date -- 1995 c 367:** See notes following RCW 77.95.150.

NEW SECTION. **Sec. 6.** A new section is added to chapter 47.01 RCW to read as follows:

(1) The department of transportation, the department of ecology, and the department of fish and wildlife must use their existing authorities and guidance to provide a preference for the removal of existing fish passage barriers owned by cities and counties as compensatory mitigation for environmental impacts of transportation projects where appropriate.



(2)(a) The office of the governor must convene the department of transportation, department of ecology, and department of fish and wildlife, and consult with other relevant stakeholders, to develop a framework for encouraging off-site and out-of-kind local fish passage barrier mitigation that provides results that are consistent with habitat protection priorities and practical design principles, and are ecologically preferable to on-site mitigation.

(b) The implementation of this framework must:

(i) Not delay transportation project delivery;

(ii) Not be additive to the amount or cost of mitigation required under existing regulations;

(iii) Not preclude on-site or off-site and in-kind mitigation when that is the most ecologically appropriate means to address project impacts;

(iv) Not alter the mitigation sequencing principles of first avoidance and the minimization of impacts before compensatory mitigation;

(v) Provide for a mechanism that identifies whether environmental impacts from projects are appropriate for local fish passage barrier mitigation;

(vi) Use the statewide fish passage barrier removal strategy developed by the fish passage barrier removal board created in RCW 77.95.160 and information provided by salmon recovery regional organizations and local entities to identify specific priority locations where removal of local barriers would provide a net resource gain; and

(vii) Consistent with existing mitigation regulations and guidelines, provide a preference, where appropriate, for investment in local fish passage barrier removal where greater environmental benefit can be achieved with off-site and out-of-kind mitigation.

(c) In addition to the framework developed in (a) of this subsection, the department of transportation, department of ecology, and department of fish and wildlife must develop and implement an umbrella statewide in lieu fee program or other formal means to provide a streamlined mechanism to undertake priority local fish passage barrier corrections throughout the watersheds of the state as a preferred means of compensatory mitigation, where appropriate, for state transportation that is consistent with the principles in (a) and (b) of this subsection.



(3) This section is not intended to decrease funding or to impede the state's efforts to meet its obligation for fish barrier correction according to existing law or court ruling

# Enhancing ecosystem restoration efficiency through spatial and temporal coordination

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**In many large ecosystems, conservation projects are selected by a diverse set of actors operating independently at spatial scales ranging from local to international. Although small-scale decision making can leverage local expert knowledge, it also may be an inefficient means of achieving large-scale objectives if piecemeal efforts are poorly coordinated. Here, we assess the value of coordinating efforts in both space and time to maximize the restoration of aquatic ecosystem connectivity. Habitat fragmentation is a leading driver of declining biodiversity and ecosystem services in rivers worldwide, and we simultaneously evaluate optimal barrier removal strategies for 661 tributary rivers of the Laurentian Great Lakes, which are fragmented by at least 6,692 dams and 232,068 road crossings. We find that coordinating barrier removals across the entire basin is nine times more efficient at reconnecting fish to headwater breeding grounds than optimizing independently for each watershed. Similarly, a one-time pulse of restoration investment is up to 10 times more efficient than annual allocations totaling the same amount. Despite widespread emphasis on dams as key barriers in river networks, improving road culvert passability is also essential for efficiently restoring connectivity to the Great Lakes. Our results highlight the dramatic economic and ecological advantages of coordinating efforts in both space and time during restoration of large ecosystems.**

freshwater | conservation | connectivity | prioritization

Habitat loss and fragmentation are leading drivers of declining biodiversity and ecosystem services worldwide (1–3). Landscape corridors and dam removals are popular and effective strategies for mitigating fragmentation (4, 5). To implement these projects efficiently, societies around the world are developing regional and even continental-scale plans for restoring ecosystem connectivity (6). These plans set ecosystem-level conservation objectives and identify priority regions for investment, but individual project selection (e.g., a specific dam removal or habitat corridor) is generally dictated by opportunism and politics. When poorly coordinated, these piecemeal mitigation efforts may be an inefficient means of achieving ecosystem-level objectives. Transboundary coordination is known to increase the cost-effectiveness of nature reserve networks (7–9), but the benefits of coordination are likely to be even greater for connectivity efforts in rivers because the dendritic nature of drainage basins makes them highly susceptible to fragmentation (10–12). Migratory fishes, which support major fisheries and ecosystem processes, are particularly vulnerable to life cycle disruption by the millions of dams and road crossings that fragment the world's rivers (13, 14).

Here, we investigate the value of coordinating restoration efforts in space and time to maximize ecological connectivity between the Laurentian Great Lakes and their tributaries. The Great Lakes Basin (GLB) contains 21% of the world's surface freshwater and is home to more than 33.5 million people (15). High societal dependence on lake-derived ecosystem services includes US$7 billion annually in economic activity related to recreational fishing (16). Historically, breeding migrations of dozens of native fish species formed an important ecological link between the Great Lakes and their tributaries (17). Today, hundreds of thousands of dams and road culverts partially or fully block historical fish migration routes (18). There is growing investment in removing or modifying these structures, but project selection has been largely opportunistic and driven by local priorities.

Barrier removal projects to restore tributary connectivity are selected and funded by a diverse set of actors operating independently at different spatial scales across the GLB. Most road crossings are managed by counties or states, whereas impacts of dams are addressed at the watershed, state, federal, or even international level. Funding to restore connectivity is often disbursed as small, one-time investments, but large pulses of public investment are occasionally available, as within the $1.2 billion Great Lakes Restoration Initiative (19). Although connectivity restoration efforts have been piecemeal, the GLB has a long history of collaborative management of shared resources, including binational treaties regarding fisheries, invasive species, and water quality (20). The success of these initiatives demonstrates that large-scale coordination is feasible and that large pulses of spending can be arranged when justified.

We used a return-on-investment framework to analyze potential efficiency gains from coordinating barrier removals at a range of spatial scales (county, tributary, state, lake, nation, or GLB-wide) and temporal scales (a single "pulse" of investment vs. the same amount allocated as a series of 2, 5, or 10 "trickle" investments). Return-on-investment approaches are known to outperform alternative strategies such as purely minimizing

## Significance

Societies around the world make massive investments in ecosystem restoration projects to mitigate habitat loss, conserve biodiversity, and boost ecosystem services. We use a return-on-investment framework to assess the value of coordinating restoration efforts in space and time to maximize ecological connectivity between the Laurentian Great Lakes and their tributaries, which are fragmented by hundreds of thousands of dams and road crossings. We show that coordinating restoration efforts across the entire region is nine times more cost-effective than local-scale planning. Similarly, a single lump sum investment is up to 10 times more cost-effective than a series of annual allocations. These dramatic economic and ecological efficiencies provide ample incentive for coordinating conservation efforts across broad spatial and temporal scales.

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cost, and maximizing benefit irrespective of cost (21). Our mathematical optimization model identifies the portfolio of barrier removal projects that provides the greatest increase in total tributary channel length (hereafter "habitat") accessible to migratory fishes for a given budget. Channel length serves as a surrogate for gains in spawning habitat across the entire fish community and is widely used in restoration planning in lieu of high-resolution spawning habitat maps for individual species.

We applied this model to a comprehensive barrier inventory for the GLB, encompassing 6,692 dams and 232,068 road crossings georeferenced within the 661 largest tributary watersheds (18). For each of these structures, we estimated the direct economic cost of restoring full passability (removal of dams or retrofitting road culverts) and the net upstream habitat that would become available, and we used estimates of the current passability of each culvert (22). Barrier passability is defined as the proportion of fish able to pass through or over a barrier to migrate upstream. Because dozens of partially passable structures often separate headwater spawning grounds from the Great Lakes, we calculated the net probability that a migratory fish could reach the area upstream of a particular barrier as the product of that barrier's passability and the passability of all downstream barriers (hereafter, the "cumulative passability" of a barrier). Similarly, the net benefit of any barrier removal includes not only full access to the unobstructed area immediately upstream but also partial access to areas above successive upstream barriers until cumulative passability declines to zero.

## Results and Discussion

Across the basin, we find that the cumulative passability of dams and road crossings is remarkably low: less than 14% of tributary channel length is fully accessible to migratory fishes (Fig. 1). Cumulative passability is typically much lower than the passability of individual road crossings, highlighting the need for a riverscape perspective in restoration planning.

Our optimization model shows that barrier removals can efficiently restore access to tributary habitat, but only when prioritized strategically. When investments were optimized for the entire basin—the most cost-efficient spatial scale of decision making—the amount of habitat accessible to migratory fishes could be doubled for $70 million (Fig. 2*A*) by restoring fish passage at 299 dams and 180 road crossings at an average individual cost of $200,000 and $57,000, respectively. Both dam and road- crossing projects are critical components of efficient strategies, with road crossings becoming increasingly important at higher levels of investment (Fig. 2*B*). Failure to consider both classes of barriers leads to striking inefficiencies: optimizing removal of only dams created access to 24% less habitat than addressing both dams and road crossings jointly across the GLB, whereas prioritizing road crossings alone was 88% less efficient (*SI Methods*).

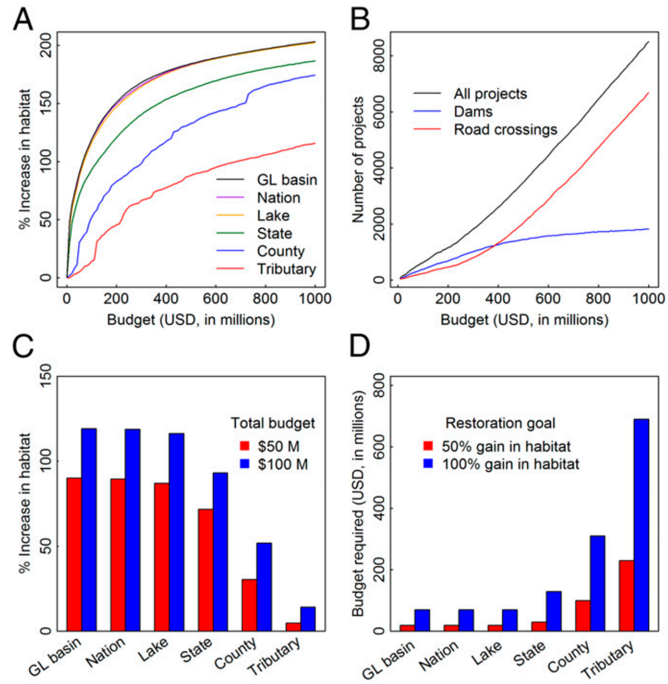


**Fig. 2.** (*A*) Return-on-investment curves for six spatial scales of coordination. (*B*) Number of dams, road crossings, and total projects in the whole-basin solution portfolios. (*C*) Increase in habitat that could be achieved with an investment of $50 million or $100 million at six spatial scales of coordination. (*D*) Budget required to achieve a 50% or 100% increase in habitat at each spatial scale.

Considering the spatial scale of project selection, the cost efficiency of barrier removal was relatively unaffected by optimizing at the national or lake scales rather than the entire GLB, but declined dramatically when investments were optimized separately for each state, county, or tributary (Fig. 2*A*). For an investment of $100 million, for example, a portfolio of projects optimized for the entire GLB would provide a 119% increase in habitat (Fig. 2*C*). Dividing the same $100 million among tributaries would provide only a 14% increase in habitat even when optimized within each watershed. Correspondingly, to double the accessible tributary length, $70 million is needed if coordinated across the GLB or divided among the five lakes, but $690 million would be required if barrier removals were optimized for each tributary individually (Fig. 2*D*). In these analyses, funding to each spatial unit was proportional to the number of barriers it contained. Results were similar for alternative distribution rules (*SI Methods*).

The allocation of restoration funding through time also proved critical; a one-time pulse of investment is much more efficient than providing the same amount in an annual trickle when funds are divided among small spatial units (Fig. 3*A*). However, when site selection was optimized for the GLB or states, there was little difference among the return-on-investment curves for a pulse vs. a trickle of investment. For $100 million delivered as a pulse to counties, accessible habitat could be increased by 52%,

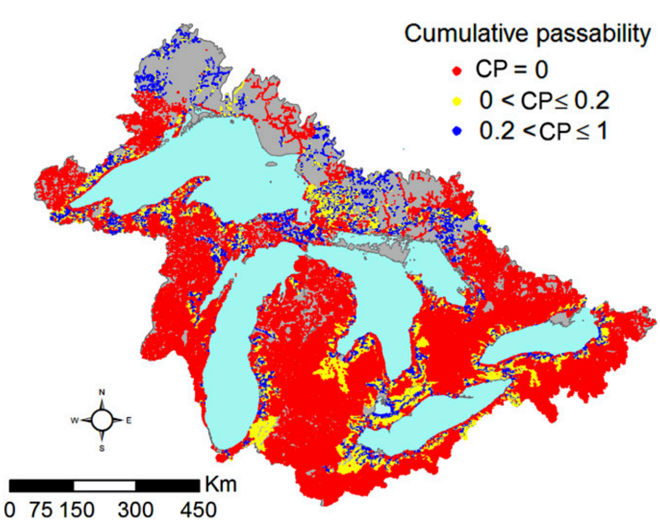


**Fig. 1.** Cumulative passability (CP) of 6,692 dams and 232,068 road crossings in the GLB. Nearly 87% of the total river channel length is at least partially inaccessible to adfluvial fishes (CP < 1), including 64% that is entirely inaccessible (CP = 0). Gray background represents areas without barriers or lacking barrier data.

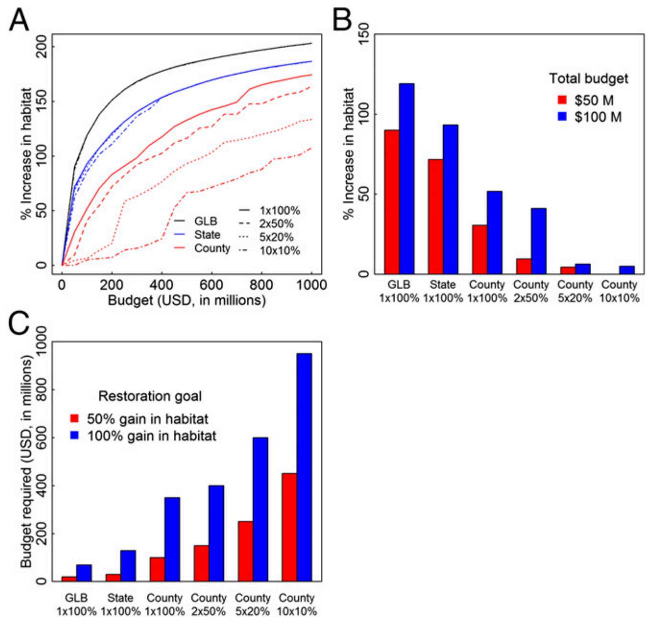


**Fig. 3.** (*A*) Return-on-investment curves for all combinations of three spatial and four temporal scales of coordination. Temporal coordination scenarios represent the entire budget allocated as a single pulse of investment (labeled 1 × 100%) vs. the same total amount allocated as a series of 2, 5, or 10 trickle investments, during which 50%, 20%, or 10% of the total budget is disbursed per funding cycle (labeled 2 × 50%, 5 × 20%, and 10 × 10%, respectively). Note that temporal curves overlap at GLB and State spatial scales. (*B*) Increase in habitat that could be achieved with an investment of $50 million or $100 million for six space by time allocation scenarios. (*C*) Budget required to achieve a 50% or 100% increase in habitat for six space by time allocation scenarios.

whereas the same amount provided as a series of annual investments over a decade would return only a 5% increase (Fig. 3*B*). To obtain a 100% increase in habitat, $350 million would be required for the county-pulse model, whereas $950 million would be required for the county-trickle model (Fig. 3*C*).

Differences in cost efficiency across spatial and temporal scales of allocation are driven by two factors. First, when the total budget is divided among spatial units (e.g., counties), some funding is inevitably directed toward areas that lack high-return projects. Thus, a purely local-scale model of planning, in which each spatial unit receives an equitable share of funding, can inadvertently force funds to be spent on inefficient projects. Similar trade-offs between equity and conservation outcomes exist for marine protected areas (23). Second, when the budget is finely divided in space and time, only a subset of possible projects are affordable, which sharply constrains aggregate efficiency. For example, a total budget of $300 million allocated under the county-scale, annual trickle model yields an average of just $123,000 per year per county, making 79% of dams (Fig. 4*A*) and 23% of road crossings unaffordable regardless of potential habitat gains (Fig. 4*B*).

Our analyses offer two key lessons that elucidate how regional coordination and collaboration can boost the efficiency of large-scale restoration efforts. First, we find that large-scale, transboundary coordination can be dramatically more efficient than even optimized local-scale planning. Interestingly, several intermediate spatial scales of coordination (nations and lakes) were nearly as efficient as whole-basin coordination. In the GLB, a variety of conservation and management issues are coordinated at the federal, state, and lake levels (20). Such intermediate-sized planning units may be a useful compromise that offers most of the economic efficiency of large-scale planning while facilitating consideration of local and regional management goals and logistical constraints (24). Our findings differ from those pertaining to the design of nature reserve networks, where international coordination has been shown to be two to three times more cost-effective than national-level coordination (7–9). This difference likely arises from the nature of the targets; reserve networks designed to maximize coverage of a list of species inevitably become more efficient when biodiversity targets can be met jointly across geopolitical units. In contrast, the target in our analyses is simply gains in access to upstream habitat, regardless of which unit they occur in or what species benefits. Presumably, the efficiency of meeting connectivity targets for multiple species would be lower at the lake and nation scales than for the entire GLB if species distributions were taken into account.

The second lesson is illustrated by the extreme inefficiency of local-scale planning when combined with annual trickle budgets. This inefficiency arises when annual budgets are not large enough to remove key dams that are both expensive and occur low in a tributary, thereby forcing expenditure on low-cost, low-reward projects. Where planning at a local scale is essential (e.g., within a high-priority watershed), some of this inefficiency could be mitigated by a one-time strategic pulse of investment sufficient to complete an expensive project. Subsequent trickle investments could then boost overall returns through relatively inexpensive road-crossing upgrades. Policy makers should, therefore, ensure that allocation levels are sufficient to afford certain expensive high-priority projects within their jurisdiction and that funding is allocated toward projects that specifically leverage other completed or planned barrier removals.

The GLB has a long tradition of binational management of shared resources, suggesting that transaction costs associated with coordination (7) would be modest and that large-scale coordination is feasible. Existing binational treaties (e.g., the Great Lakes Water Quality Agreement), institutions (e.g., the Great Lakes Fishery Commission), and interagency agreements [e.g., the Joint Strategic Plan for Management of Great Lakes Fisheries (20)] are important precedents for basin-wide coordination to address key conservation issues. Indeed, formal and informal frameworks for coordinating investments in connectivity across the GLB are beginning to emerge. Given the growing focus on barrier removals by a large number of local, state, federal, and nongovernmental organization actors, our findings underscore the benefits of a collaborative framework for prioritizing investments in connectivity across the GLB.

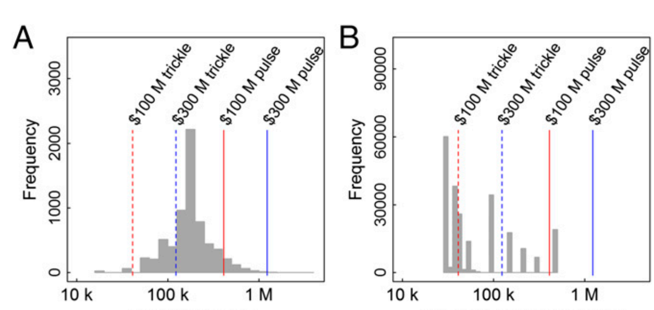


**Fig. 4.** Costs of barrier removal relative to funding levels under various spatial and temporal allocation scenarios. (*A*) For dam removal, the frequency histogram of project costs is compared with per-county budgets under four scenarios: $100 million total budget allocated among counties as a series of 10 annual investments (a 10 × 10% trickle approach), $300 million trickle, $100 million allocated as a single pulse, and $300 million pulse. Vertical line position on the horizontal axis marks the funding available to each county under each of the four scenarios. (*B*) For road crossings, retrofitting costs are compared with the same four budget scenarios.

Although our analyses focused on coordination for ecological objectives only, the political realities of infrastructure maintenance may also create opportunities for cost-efficient conservation investments. All infrastructure has a finite life span, and proper maintenance is costly in aggregate. Future investments in maintenance or replacement of dams and road crossings will come from many sources with various objectives, but ecological outcomes will generally be secondary to public use and safety issues. Thus, a promising conservation strategy is to leverage ongoing infrastructure maintenance activities by supporting low-cost, high-return add-ons to infrastructure projects that are already underway for other reasons (18, 25). In addition, using ecological restoration value as a tie-breaker in selection of infrastructure projects might enhance connectivity at no cost whatsoever.

We stress that large-scale coordination does not necessitate purely top-down, centralized planning. Self-organized or facilitated cooperation among local actors can represent a form of large-scale planning, but one that leverages the local resources and expertise that can be crucial for on-the-ground restoration success. In the GLB, numerous locally driven initiatives play essential roles in conservation efforts (24). Large-scale prioritization could complement local efforts by establishing overarching conservation targets and ensuring that individual projects align in ways that reconnect isolated habitats and populations (24, 26, 27). Moreover, we recognize that local-scale decision making is often rooted in unpredictable reductions in the economic or sociopolitical costs of a particular project. Such opportunities can be entirely worthwhile even if they were not prioritized when using standardized cost data.

Our model does not account for tributary habitat conditions, the spatial distribution of beneficiary species, or the likelihood of species invasions, all of which mediate the ecological benefits of barrier removals (28, 29). Unfortunately, these important management considerations have not been systematically mapped across the entire GLB, so they cannot be incorporated into current optimization models. However, previous work elsewhere suggests that, in some cases, project selection is less sensitive to the distribution of beneficiary species than to spatial variation in project costs (30). We also recognize that the decision to remove a specific barrier often involves multiple stakeholders with differing social and economic values and perspectives (31). Although socioeconomic factors often have enormous importance in individual project selection (32), this perspective is difficult to quantify systematically across the entire GLB for purposes of conservation planning. Nevertheless, our general findings on the relative efficiency of large-scale planning are likely to be robust to further consideration of the ecological costs and benefits of particular barrier removals due to statistical averaging of these costs and benefits over the enormous number of barriers in our analysis. Thus, it is unlikely that refining our estimates of removal costs, habitat gains, or other factors would alleviate the disparities in relative cost efficiency between large- and small-scale project selection, or pulsed and trickled funding patterns.

Given that most of the world's large freshwater and terrestrial ecosystems are heavily fragmented (13, 33), our finding that spatial and temporal coordination is critical for maximizing returns on societal investments in restoring connectivity is relevant in many conservation contexts. Moreover, the same concepts and mathematical tools could be applied proactively to minimize the impacts of new roads and dams (34–36). This is a critical conservation problem given estimates that the global road network will increase 60% in length between 2010 and 2050 (36). Similarly, our approach could be adapted to identify cases where it would be beneficial to retain existing barriers or construct new barriers to inhibit the spread of invasive species and pathogens (37). In the GLB, for example, more than 60 barriers have been constructed or modified to control the spread of invasive sea lampreys (38). Optimization models can also be expanded to account for risk of infrastructure failure or habitat loss under climate change (39). In each of these contexts, our results on restoring aquatic connectivity, and previous work on transboundary coordination in nature reserve networks (7–9), illustrate the benefits of coordinating investments in both space and time. These dramatic economic and ecological efficiencies provide ample incentive for coordinating restoration efforts across broad spatial and temporal scales.

## Methods

**Optimization Model.** We developed a mathematical optimization model that, for a given budget, identifies the portfolio of barrier removal projects that provides the greatest net increase in accessibility-weighted tributary habitat available to migratory fishes. Barrier passability is defined conceptually as the proportion of fish able to pass through or over a barrier while migrating upstream (11). We define the cumulative passability of a barrier as the product of that barrier's passability and the passability of all downstream barriers. Cumulative passability thus represents the probability that a fish can migrate between the Great Lakes and the tributary channel immediately upstream of a barrier. This is equivalent to the definition of "accessibility" in ref. 11. In calculating cumulative passability, we treat successive passage events as independent, which is typical in fish passage prioritization analyses (12). It is not our intent to address performance differences among individual fish based on swimming ability. For the strongest individuals, our passability ratings would be underestimates, or if fatigue leads to diminishing swimming ability with each barrier passed, then our cumulative passability ratings would be overestimates.

Our model extends that of ref. 11 to account for differences in barrier passability ratings and upstream habitat length for multiple species. Specifically, we consider a set of fish guilds, where a guild represents a group of species exhibiting similar swimming abilities and thus having similar likelihood of being capable of passing a particular barrier.

In this study, we only consider projects that restore full passability to a barrier location. We also assume that each barrier has only a single proximate downstream barrier. Our formulation thus omits braided channels, deltas, and artificial connections via drainage channels. This modest simplification is essential for model tractability and captures the large majority of tributary network patterns in our study area.

Given the following decision variables:

$$x_j = \begin{cases} 1 & \text{if artificial barrier } j \text{ is removed (i.e., restored to full passability)} \\ 0 & \text{otherwise} \end{cases},$$

our mathematical formulation of the fish passage barrier removal problem is as follows:

$$\max \sum_{j\in J}\sum_{g\in G} h_{jg}\alpha_{jg} \qquad [1]$$

s.t.

$$\alpha_{jg} = \prod_{k\in D_j}\left(p^0_{kg} + p_{kg}x_k\right) \qquad \forall j\in J, g\in G \qquad [2]$$

$$\sum_{j\in J^{Art}}\sum_{r\in R} c_j x_j \le b_r \qquad \forall r\in R \qquad [3]$$

$$x_j \in \{0,1\} \qquad \forall j\in J^{Art} \qquad [4]$$

Here, $G$ is the set of all fish guilds, indexed by $g$; $J$ is the set of all natural and artificial barriers, indexed by $j$; $J^{Art}$ is the subset of artificial barriers; $D_j$ is the set of all barriers downstream from and including $j$; $R$ is the set of planning regions, indexed by $r$; $h_{j,g}$ is the net amount of habitat for guild $g$ between barrier $j$ and its immediate upstream barriers or the range limit for guild $g$, in stream kilometers; $p^0_{jg}$ is the initial passability for guild $g$ at barrier $j$; $p_{jg}$ is the increase in passability for guild $g$ given mitigation of barrier $j$; $c_j$ is the cost of mitigating barrier $j$, in US dollars; $b_r$ is the available budget for region $r$, in US dollars; and $\alpha_{jg}$ is the cumulative passability (i.e., accessibility) of barrier $j$ for guild $g$.

The objective function [**1**] maximizes total accessibility-weighted habitat upstream of each barrier $h_{jg}\alpha_{jg}$, over all barriers $j\in J$ and guilds $g\in G$. We weighted all guilds equally for the analyses in this paper. Eqs. **2** give the cumulative passability $\alpha_{jg}$ of barrier $j$ for guild $g$. The passability for guild $g$ at any intervening barrier $k$ in set $D_j$ is simply equal to the initial passability $p^0_{kg}$ for guild $g$ plus the potential increase in passability $p_{kg}x_k$ for guild $g$ given mitigation of barrier $k$. Multiplying the passability of all barriers in $D_j$ yields the cumulative passability of barrier $j$ for guild $g$. Inequalities [**3**] specify that the sum of the project costs within a given planning region $r$ cannot exceed the available budget $b_r$ allocated to that region. We modeled budget allocations $b_r$ as proportional to the number of barriers in a region (results in Figs. 2–4) or proportional to human population (results in *SI Methods*). Leftover funds were not carried over to other planning regions or time periods. Last, constraints [**4**] specify that all barrier mitigation decision variables must be binary.

Note that the above model is nonlinear. An exact linear formulation of the problem was devised by introducing a series of probability chains (40) to evaluate cumulative passability terms [**2**]. A probability chain is a newly proposed technique from the operations research field for linearizing certain classes of high-order polynomial terms such as [**2**]. See *SI Methods* for linearization methods and an example return-on-investment analysis using a small fish passage barrier network.

**Data and Submodels.** Here, we describe data and submodels for the calculation of project costs, passability, and upstream habitat for each of the 238,760 potential barriers in our analysis. For these calculations, we derived geomorphic and road network covariates from widely available spatial datasets using ArcGIS 10.2 (41). We obtained road surface type (paved or gravel/dirt) and road class (interstate highway, regional highway, or local road), where available, from the US Census Bureau's TIGER roads layer (42) and Land Information Ontario's Ontario Road Network (43). We estimated road width by assuming that interstate highways are six lanes wide, regional highways are four lanes wide, and local roads are two lanes wide, and that these three road classes have widths of 25.6 m (84 ft), 18.3 m (60 ft), and 11 m (36 ft), respectively. The stream polylines are a merged dataset derived from the US Geological Survey's National Hydrography Dataset (44) and the Canadian National Hydro Network (45). To ensure all stream network polylines were strictly dendritic, we manually removed braided and artificial channels and then used the Check Network Topology tool in FLOWS, version 9.3 (46), using ArcGIS 10.2. We calculated upstream drainage area at each barrier using a 30 × 30-m digital elevation model (47).

Our database of 238,760 structures is a subset of the 276,027 dams and road crossings reported in ref. 18. Our dataset is smaller because we omit barriers on very small drainages that drain directly to the Great Lakes. These smallest drainages were omitted because most barrier removal projects focus on larger tributaries that host spawning migrations of a wider range of species. Although the source barrier dataset is the most comprehensive available for the GLB, it also omits natural barriers (e.g., waterfalls) and dams and road crossings that have not been mapped in federal or state databases. These additional barriers may reduce realized habitat gains relative to those reported here. These data gaps are likely to be systematic, however, such that our core findings on the relative efficiencies of planning at different spatial and temporal scales still hold.

**Project Cost.** For each of the 238,760 structures in our analysis, we used data on completed project costs (for dams) or estimates of material, labor, and personnel costs (for road crossings) to predict the cost of restoring full passability at a structure. Specifically, we model the cost of removing a dam or the cost of replacing a road-crossing structure with a "fish-friendly" culvert or bridge.

To estimate dam removal costs, we used data from 108 completed dam removal projects in the GLB compiled by American Rivers, a nonprofit organization. Completed projects spanned the period 1965–2013, with 95 of 108 dam removals completed after 1990. To represent historical project costs in 2012 US dollars, we used the Consumer Price Index, an index of inflation published by the US Bureau of Labor Statistics (48). After converting historical project costs to 2012 US dollars, we created a statistical model to predict the cost of removing a dam based on characteristics of that dam. Because our aim was to apply this model to the majority of the 6,692 dams in our dataset, we used as model covariates only those that were widely available for the majority of the dams in the GLB. Dam height was the most consistently available attribute, available for ~75% of dams in our database. Although dam age, purpose and ownership are often important determinants of removal cost, this information is available for only a small subset of the dams in the GLB. Furthermore, we focused solely on infrastructure costs; we did not consider costs associated with removing or mitigating contaminated impounded sediments (4, 29), or the ecological and economic costs of suppressing species invasions into the newly accessible habitat. Accounting for these additional costs could potentially alter the balance of road crossings and dams in optimal project portfolios.

To predict dam removal costs using dam height, we fit a simple linear regression model ($R^2 = 0.30$) to relate dam removal costs, in 2012 US dollars, to the $\log_{10}$ of dam height, in meters:

$$\log_{10}(\text{cost}) = 4.74 + 0.94 \times \log_{10}(\text{height}).$$

We then used this equation to predict dam removal costs for each of the 4,897 dams in our dataset with recorded field-measured height data. For the 1,795 dams for which we had no height information, we assumed that the median dam removal cost (US$173,032.50) was applicable in lieu of height data. To test whether this assumption affected our results, we compared the value of the objective function calculated using the median dam removal cost to the values of the objective when replacing these cost estimates with one of eight different values in the range $113,000 (representative of a dam 2.13 m tall) to $261,000 (representative of a dam 5.22 m tall). The differences in objective function values were less than 1% in all cases, except for the first scenario (setting the removal cost of these 1,795 dams to $113,000), which was 1.3% different from the results in Fig. 2.

Dams for which we had no height data are very unlikely to be large dams with a removal cost greater than $261,000. Our database includes height data for all GLB dams within the US National Inventory of Dams, which is stated to include all dams that are equal to or greater than 6 ft (1.83 m) in height and 50 acre-feet (61.7 ML) in storage, as well as all dams that are equal to or greater than 25 ft (7.62 m) in height and exceed 15 acre-feet (18.5 ML) in storage.

For each of the 232,068 road crossings in our analysis, we used data on material and personnel costs to estimate the total cost of replacing the road-crossing structure with a fish-friendly culvert or bridge. The main drivers of project costs are stream width, road width, road fill depth, and road surface. Details are presented in *SI Methods*.

**Upstream Habitat.** For each of the 238,760 structures in our analysis, we estimated the amount of habitat upstream of that structure by measuring the net tributary length ($h_{jg}$ in the model) between each structure and its nearest set of upstream structures. For this calculation, we used RivEX (49) and ArcGIS 10.2 (41) to sum the distance of all upstream polylines up to the closest set of upstream structures or the river source.

We chose to use tributary length as a measure of habitat because it is a simple metric that integrates restoration benefit across the community of native beneficiary species, whose preferred habitat is patchy and spatially variable across the GLB. Analyses aimed at generating restoration plans for particular species or groups of species are possible using our model by replacing tributary length with more specific estimates of the amount and quality of each habitat type. In each case, the set of priority barriers identified will depend on the set of species chosen and the weightings assigned to those species.

**Structure Passability.** We assumed that all dams in our analysis had zero passability and that removing a dam would restore full passability. Although a small subset of dams may in reality be partially passable to certain fishes (due to low height or having a fish passage structure), passability data for dams are not consistently available across the GLB. Fish passage structures are absent from most dams in the GLB, and even where present, salmonid-inspired passage structures may not work well for the weak leapers that dominate the native migratory fish assemblage (50).

For road crossings, we assumed that all intersections with streams of Strahler order >4 were likely to be bridges (22) and therefore fully passable to migratory fishes (~7.4% of the road crossings in our analysis). For structures over streams with a Strahler order ≤4, we used structure-specific passability estimates from ref. 22. In brief, field-surveyed data from 2,235 culverts across nine watersheds in the GLB were used to create a statistical model linking culvert passability to geographic information system (GIS)-derived landscape geomorphic covariates. In this model, the passability of a culvert is the product of two independent dimensions, culvert outlet drop and culvert outlet water velocity, each of which is estimated independently using a boosted regression tree model. The predictive power of these models as measured by the area under the receiver operating characteristic curve ranged from 0.64 to 0.69, suggesting reasonable ability to predict passability of road crossings from GIS-derived landscape covariates.

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# Supporting Information

## Neeson et al. 10.1073/pnas.1423812112

### SI Methods

#### Linearization of the Optimization Model

To solve the nonlinear optimization model presented in the main text, an exact linear formulation of the problem was devised by introducing a series of probability chains (1) to evaluate cumulative passability terms [**2**]. Specifically, if we introduce the following auxiliary variables:

$\lambda_{jg}$ = change in cumulative passability for guild $g$ given mitigation of barrier $j$

and let $d_j$ denote the barrier immediately downstream from barrier $j$, Eq. **2** can be replaced with the following set of linear constraints.

$$\alpha_{jg} = p^0_{jg} + \lambda_{jg} \qquad \forall j \in J | d_j = \varnothing, g \in G \qquad \textbf{[S1]}$$

$$\alpha_{jg} = p^0_{jg}\alpha_{d_j g} + \lambda_{jg} \qquad \forall j \in J | d_j \neq \varnothing, g \in G \qquad \textbf{[S2]}$$

$$\lambda_{jg} \le p_{jg} x_j \qquad \forall j \in J^{Art}, g \in G \qquad \textbf{[S3]}$$

$$\lambda_{jg} \le p_{jg}\alpha_{d_j g} \qquad \forall j \in J^{Art} | d_j \neq \varnothing, g \in G \qquad \textbf{[S4]}$$

Eqs. **S1** and **S2** determine, respectively, the cumulative passability for barriers having no downstream barrier and the cumulative passability for barriers located above one or more barriers. Inequalities **S3** and **S4**, meanwhile, place bounds on the allowable increase in cumulative passability $\lambda_{jg}$ for guild $g$ given mitigation of barrier $j$. Collectively, [**S1–S4**] allow cumulative passability $\alpha_{jg}$ as well as any increase in cumulative passability $\lambda_{jg}$ at barrier $j$ to be determined in a recursive manner by basing it on the cumulative passability $\alpha_{d_j g}$ of barrier $j$'s downstream barrier.

The linear version of the fish passage barrier removal problem was coded in the General Algebraic Modeling System (GAMS). GAMS is a high-level modeling language for formulating linear optimization problems (2). The GAMS implementation of our model was solved using the CPLEX commercial solver, which employs a branch-and-bound algorithm to solve mixed integer linear programs like the one we consider here.

#### Example Return-on-Investment Analysis

Consider the river network illustrated in Fig. S3 and associated barrier data provided in Table S1. In this example, two dams (barriers 2 and 5) and three road crossings (barriers 1, 3, and 4) fragment a small river network. These five barriers differ in their initial passability ($p^0_{jg}$), upstream habitat ($h_{jg}$), and cost to restore full passability ($c_j$). As in the analysis presented in the main text, we consider three migratory fish guilds, indexed by $g$ = 1, 2, 3.

We performed a return-on-investment analysis using the example river network for nine budgets ranging from \$0 to \$800,000 (Table S2). For a budget of \$0, no barriers are removed and the total accessibility-weighted habitat above barriers in the river network (i.e., 355.50 km, the initial value of the objective function [**1**]) is calculated using the initial passabilities of each barrier. For a budget of \$100,000, the optimal decision is to remove barrier 3. Removing barrier 3 restores full passability at that location for all three migratory fish guilds, and the resulting total accessibility-weighted habitat in the river network rises to 432.00 km. The percentage increase in habitat that results from removing barrier 3 is calculated by subtracting the initial value of the objective function (i.e., 355.30 km) from the value of the objective function when barrier 3 is removed (i.e., 432.00 km) and dividing by the initial value. Removing barrier 3 thus results in a 21.6% increase in the amount of habitat in the river network.

A budget of \$200,000 results in a moderate further increase in habitat (a 28.3% increase over the initial state) via the removal of barriers 3 and 5. A budget of \$300,000, however, results in a much larger increase in habitat (a 114.6% increase over the initial case) because it is now possible to remove barrier 2, an expensive dam that was initially completely impassable.

For a budget of \$800,000, all five barriers may be removed. In that case, the entire river network becomes fully accessible to migratory fishes and the total accessibility-weighted habitat in the river network is the total tributary length above barriers summed across all three guilds (i.e., 1,095.00 km).

This example (Table S2) illustrates several key aspects of return-on-investment analyses. First, the sequence of projects selected is nonnested, meaning that strategic switch points occur where projects favored at lower budgets are skipped in favor of others at higher budgets. Such outcomes are impossible under conventional scoring-and-ranking approaches, in which individuals projects are ranked and then pursued in order until no funds remain. Second, habitat gains ("return") are a nonlinear function of budget ("investment"). As a reflection of the idiosyncrasies of both the cost and benefit of individual projects, there are occasions when unusually large gains are possible as budgets increase (e.g., stepping from \$200,000 to \$300,000 in our example). Finally, note that the model does not necessarily expend all funds at any given budget increment; it will only fund an affordable set of projects if the resulting portfolio yields the same or higher return than any other alternative.

#### Details of Road-Crossing Cost Model

For each road-crossing structure, we first estimated the bankfull width (BFW) of the stream using empirically derived regional relationships between drainage area and BFW given by ref. 3. Using GIS-derived upstream drainage area (DA) at each crossing, we calculated BFW in meters as $\log_e(\text{BFW}) = \log_e(2.45 + 0.33 \times \text{DA} \times 10^{-6})$.

For road crossings over streams with BFW greater than 24 ft, we assumed that the replacement structure would most likely be a concrete bridge. Bridge cost was estimated as \$75,000 per road lane required. For road crossings over streams with BFW less than 24 ft but greater than 12 ft, we assumed that the replacement structure would most likely be a prefabricated steel bridge, with cost estimated as \$50,000 per road lane.

For road crossings over streams with BFW less than 12 ft, we used a more detailed model to estimate the total material and personnel costs of replacing the existing structure with a fish-friendly culvert. In the equations that follow, all linear measurements are given in feet.

The total cost ($TC$) of a project was estimated as the sum of the culvert costs $c$, excavation costs $e$, surfacing costs $s$, and miscellaneous costs $m$, plus 20% for design and construction oversight:

$$TC = 1.2(c + e + s + m)$$

The culvert costs $c$ assume a 25% premium for polymer coating and \$1,000 for beveled ends, and depend on the culvert length $cl$ and the cost per foot $cpf$:

$$c = 1.25(cl \times cpf) + 1{,}000$$

Cost per foot $cpf$ was estimated based on market prices in Michigan and Wisconsin in 2009 for corrugated metal pipe arch (Table S3). We assumed 2:1 side slopes on road embankments and calculated culvert length $cl$ as a function of total fill depth $tfd$ and road width $rw$:

$$cl = 4tfd + rw$$

Total fill depth $tfd$ is the sum of the culvert height $ch$ and fill depth $fd$, plus an additional excavation of 2 ft below the stream bed to accommodate bedding and buried culvert bottom:

$$tfd = fd + ch + 2$$

Fill depth $fd$ was estimated as 4 ft for interstate and regional highways and 2.5 ft for local roads based on ~1,500 crossings surveyed in Wisconsin. Culvert height $ch$ was estimated from BFW according to Table S3.

Excavation costs $e$ were calculated as the difference between the prism volume of excavated material $pv$ and the culvert volume $cv$:

$$e = \frac{27}{20}(pv - cv)$$

We assumed that the prism volume of excavated material $pv$ would require 3-ft clearance on each side and 2-ft clearance under bottom of culvert and would depend on road width $rw$, total fill depth $tfd$, and bankfull width $bfw$:

$$pv = rw \times tfd \times (bfw + 6) + (tfd \times (bfw + 6) \times 2.5)$$

Culvert volume $cv$ is the culvert length $cl$ multiplied by the culvert end area $ca$, converted to cubic yards:

$$cv = cl \times \frac{ca}{27}$$

Surfacing costs were estimated as \$2,500 per lane for paved roads and \$800 for gravel or dirt roads. Finally, miscellaneous costs were \$2,500 for road crossings over streams with BFW less than 8 ft and \$5,000 for crossings over streams with BFW greater than 8 ft. Miscellaneous costs include the disposal of the old culvert and unsuitable fill, dewatering during construction, and construction of rip-rap embankments.

## Details of Culvert Passability Model

Culvert outlet drop was measured in the field as the distance between the culvert outlet and the stream surface. Because most native fishes in the GLB are weak leapers, we assumed that any culvert drop would be totally impassable (i.e., passability equal to zero) by all species. Culverts with no outlet drop were assumed to be passable by all species (passability equal to 1). The boosted regression tree (BRT) model estimates the probability that a particular culvert has an outlet drop, such that predicted passability in this dimension is a continuous variable ranging from zero to 1.

To estimate whether culvert water velocity would inhibit fish passage, we used water velocity thresholds for three guilds or groups of fishes that reflect swimming ability. For a group of weak-swimming fishes, which would include species such as river darters (*Percina shumardi*), we assumed that velocities greater than 0.4 m/s would be impassable (passability equal to zero), whereas water velocities below this threshold would be passable. For a group of fishes with moderate swimming abilities, such as walleye (*Sander vitreus*) and white suckers (*Catostomus commersonii*), we assumed that velocities greater than 0.7 m/s would be impassable. Finally, for a strong-swimming group, representing salmonids, we assumed that velocities greater than 1.0 m/s would be impassable. As with culvert outlet drop, the BRT model estimates the probability that a particular culvert would be a velocity barrier for fishes within each of the three swimming groups considered here.

Mean predicted culvert passability, calculated as the product of outlet drop and water velocity components, was 0.68 for the weak-swimming group of fishes, 0.77 for the moderate swimmers, and 0.80 for the strong swimmers (Fig. S4). The distribution of road-crossing passabilities for all three fish group shows strong negative (or left) skew.

## Optimization Results for Investments Weighted by Population

Here, we present optimization analyses in which funding allocations are weighted by population, rather than by the number of barriers per spatial unit as in the main text. Human population reflects tax revenue and is therefore correlated with funding available to states and counties to manage road culverts. We obtained population data for the entire GLB at a 1 × 1-km resolution from the Global Rural Urban Mapping Project (4). For each spatial unit (e.g., a county), we allocated funding to that unit proportional to the unit's population.

The population-weighted scenario yields similar results to those in the main text. Dividing investments among counties or tributaries and then optimizing these investments separately for each of these smaller units, would be much less efficient than planning at the basin, nation, or lake scales (Fig. S2*A*). For an investment of \$100 million, for example, a portfolio of projects optimized for the entire basin would provide a 119% increase in the amount of habitat accessible to migratory fishes (Fig. S2*B*). Dividing the same \$100 million among counties and optimizing priorities within each county, however, would provide only a 52% increase in habitat, whereas optimizing for each tributary would provide only a 14% increase in habitat. To obtain a 100% increase in habitat, only \$70 million would be needed at the basin scale (Fig. S2*C*), but \$510 million would be needed if priorities were optimized for each county individually and more than \$1 billion would be needed if priorities were optimized for each tributary individually.

The population-weighted allocation results differ from the results in the main text (weighting by the number of barriers) at the state/province level. Here, dividing an investment among states and optimizing priorities for each state individually was slightly more efficient than optimizing priorities for each lake individually, whereas in the main text it was slightly less efficient. This difference is attributable to variation among states in population sizes relative to number of barriers. Although this effect exists at all spatial scales, in the GLB it is most pronounced among states.

## Dams-Only and Road-Crossings–Only Return-on-Investment Scenarios

Tributaries of the Laurentian Great Lakes contain roughly 38 times as many road crossings as dams. To quantify the inefficiency that could result from failing to plan for both dam and road-crossing projects, we compared the return-on-investment curves that would result from considering only dams or only road crossings to those derived from joint analysis of both dams and road crossings (Fig. S1*A*). We found that major inefficiencies can result when restoration plans fail to account for both types of barriers. For an investment of \$100 million, for example, a portfolio of dams and road crossings could provide a 119% increase in the amount of habitat accessible to migratory fishes (Fig. S1*B*). A portfolio of dams alone, however, would provide only a 90% increase in the amount of habitat accessible to migratory fishes. A portfolio of road crossings alone would be extremely inefficient and result in only a 14% increase in habitat.

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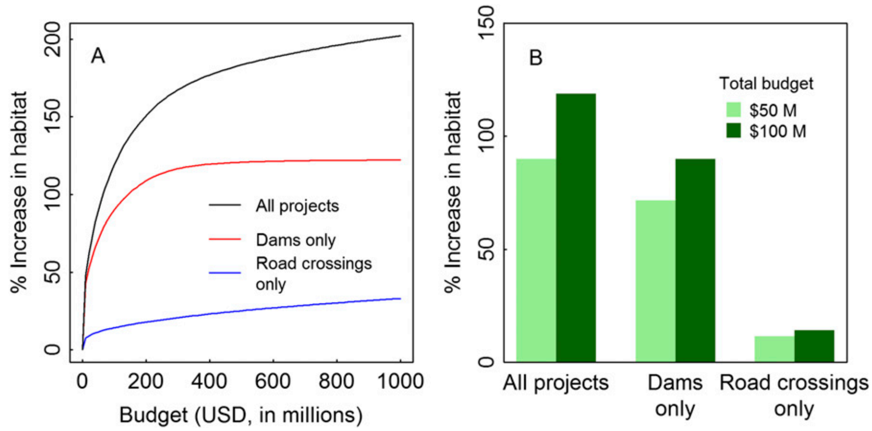


**Fig. S1.** (*A*) Return-on-investment curves for portfolios of dams and road crossings (black), dams alone (red), and road crossings alone (blue). (*B*) Increase in habitat that could be achieved with an investment of $50 million or $100 million, targeted at removing both dams and road crossings (left two columns), dams alone (middle columns), or road crossings alone (right two columns).

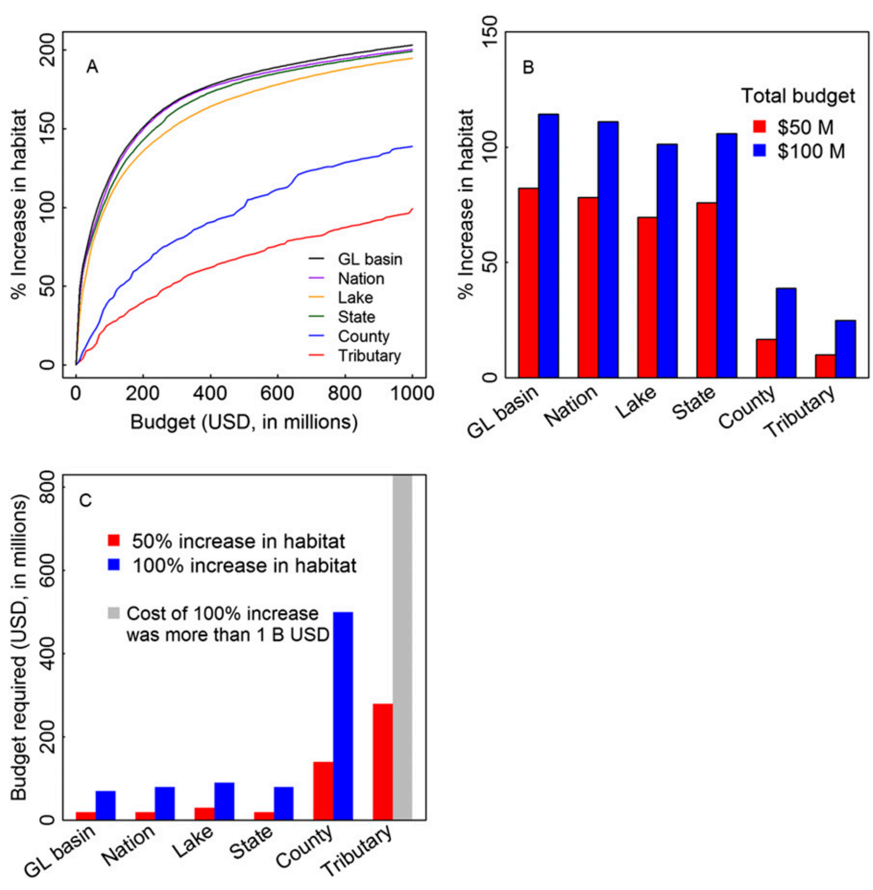


**Fig. S2.** Results of optimization analyses in which funding allocations are weighted by human population, rather than by the number of barriers per spatial unit as in the main text. (*A*) Return-on-investment curves for six spatial scales of coordination. (*B*) Increase in habitat that could be achieved with an investment of $50 million or $100 million at six spatial scales of coordination. (*C*) Budget required to achieve a 50% or 100% increase in habitat at each spatial scale.

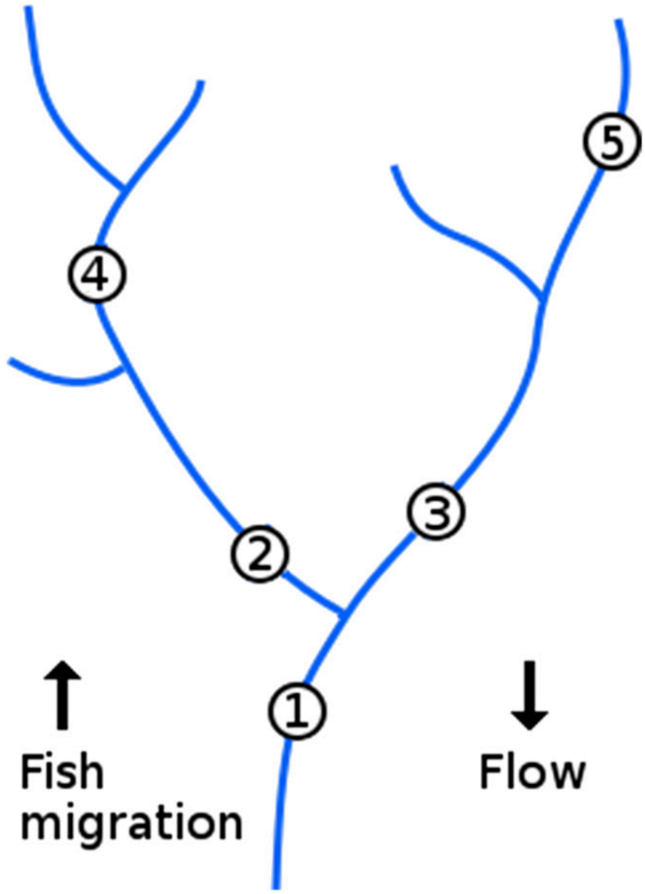


**Fig. S3.** An example river network with five fish passage barriers.

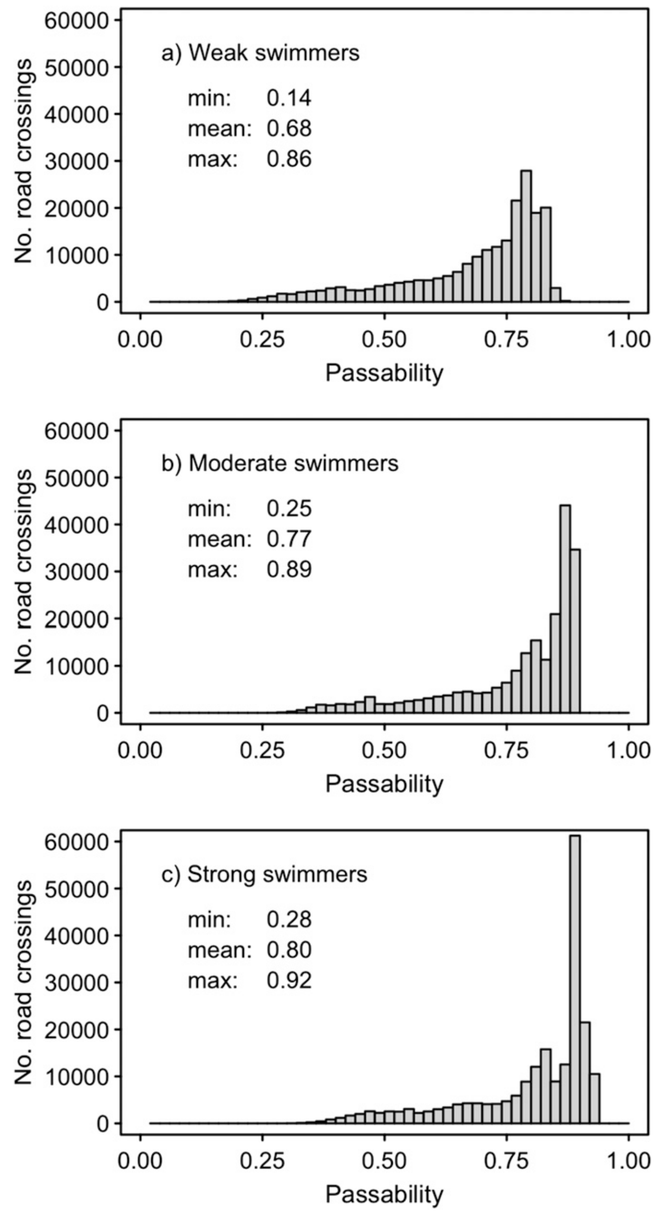


**Fig. S4.** Histograms of predicted road crossing passabilities (i.e., the product of outlet drop and water velocity passabilities) for (*A*) weak-swimming fishes, (*B*) moderate swimmers, and (*C*) strong swimming fishes. Road crossings over streams with a Strahler order >4 are assumed to be bridges (passability = 1) and so not shown.

**Table S1. Barrier data for the river network illustrated in Fig. S3**

| Barrier | Type | $p_{j1}^0$ | $p_{j2}^0$ | $p_{j3}^0$ | $h_{j1}$ | $h_{j2}$ | $h_{j3}$ | $p_{j1}$ | $p_{j2}$ | $p_{j3}$ | $c_j$ | $D_j$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Culvert | 0.9 | 0.8 | 0.7 | 50 | 50 | 50 | 0.1 | 0.2 | 0.3 | $150,000 | 1 |
| 2 | Dam | 0 | 0 | 0 | 100 | 100 | 100 | 1 | 1 | 1 | $300,000 | 1, 2 |
| 3 | Culvert | 0.8 | 0.75 | 0.7 | 130 | 130 | 130 | 0.2 | 0.25 | 0.3 | $75,000 | 1, 3 |
| 4 | Culvert | 0.95 | 0.93 | 0.9 | 75 | 75 | 75 | 0.05 | 0.07 | 0.1 | $200,000 | 1, 2, 4 |
| 5 | Dam | 0 | 0 | 0 | 10 | 10 | 10 | 1 | 1 | 1 | $60,000 | 1, 3, 5 |

**Table S2. Optimal barrier removal portfolios for nine budgets on the example river network illustrated in Fig. S3**

| Budget | Barriers removed | Habitat | Increase in habitat, % |
|---|---|---|---|
| \$0 | — | 355.30 | — |
| \$100,000 | 3 | 432.00 | 21.6 |
| \$200,000 | 3, 5 | 456.00 | 28.3 |
| \$300,000 | 2 | 762.48 | 114.6 |
| \$400,000 | 2, 3 | 839.18 | 136.2 |
| \$500,000 | 1, 2 | 951.00 | 167.6 |
| \$600,000 | 1, 2, 3, 5 | 1,078.50 | 203.5 |
| \$700,000 | 1, 2, 3, 5 | 1,078.50 | 203.5 |
| \$800,000 | 1, 2, 3, 4, 5 | 1,095.00 | 208.2 |

Habitat is the value of the objective function [**1**], i.e., the total accessibility-weighted habitat above barriers in the river network. The percentage increase in habitat is calculated relative to the initial state of the river network with no barriers removed.

**Table S3. Estimates of culvert cost per foot, end area, and height based on bankfull width (BFW)**

| BFW, ft | Cost per foot, USD | Culvert end area, $ft^2$ | Culvert height, ft |
|---|---|---|---|
| BFW $<$ 2.5 | 34.85 | 4.90 | 2.00 |
| 2.5 $\leq$ BFW $<$ 3.5 | 65.55 | 9.62 | 2.75 |
| 3.5 $\leq$ BFW $<$ 4 | 74.70 | 12.57 | 3.16 |
| 4 $\leq$ BFW $<$ 4.5 | 83.80 | 15.90 | 3.58 |
| 4.5 $\leq$ BFW $<$ 5 | 115.60 | 19.63 | 3.92 |
| 5 $\leq$ BFW $<$ 6 | 138.50 | 28.27 | 4.75 |
| 6 $\leq$ BFW $<$ 7 | 145.77 | 38.48 | 5.58 |
| 7 $\leq$ BFW $<$ 8 | 155.85 | 50.27 | 6.25 |
| 8 $\leq$ BFW $<$ 9 | 214.61 | 63.62 | 6.91 |
| 9 $\leq$ BFW $<$ 10 | 294.26 | 78.54 | 7.58 |
| 10 $\leq$ BFW $<$ 12 | 297.46 | 95.03 | 8.20 |

Cost per foot was estimated using market prices for Michigan and Wisconsin in 2009 for corrugated metal pipe arch. Culvert end area assumes existing culvert is round. Culvert height assumes dimensions of standard pipe arch culvert.