Fish Passage Project Prioritization

Bibliography

Hope Shinn, Librarian, NOAA Central Library

NCRL subject guide 2020-13
https://doi.org/10.25923/7d07-zt83

December 2020

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Office of Oceanic and Atmospheric Research
NOAA Central Library – Silver Spring, Maryland

Table of Contents

Background & Scope

NOAA Fisheries is looking at ways to better implement their programs that use fish passage. One way to better implement the fish passage work is through the prioritization of fish passage projects. This annotated bibliography collects literature on the prioritization of fish passage projects throughout the world, but with a focus on the parts of the United States under NOAA Fisheries' jurisdiction. The bibliography is arranged in two sections; the first covers specifically fish passage project prioritization, and the second section covers other kinds of natural resource prioritization literature that was found to be relevant.

Section I – Fish Passage Prioritization

This section includes academic and grey literature on fish passage prioritization projects, their methods, and outcomes. It is further separated into the following broad geographic groups, according to the focus location of the paper: Australia; Western North America; Eastern North America; Great Lakes; South America; and Europe; there is one final group for papers that have no focus location.

Section II – Other

This section includes academic literature on the topic of natural resource prioritization that was found to be relevant to fish passage, without being strictly on that topic.

Sources Reviewed

The following databases were used to identify sources: Clarivate Analytics' Web of Science: Science Citation Index Expanded and Social Science Index; Science.gov; ProQuest's Science and Technology including Aquatic Science Fisheries Abstracts; Elsevier's Science Direct; JSTOR; EBSCO's Academic Search Complete and Environment Complete; NOAA's Institutional Repository; BioOne Complete; and Google Scholar.

Section I: Fish Passage Prioritization

Australia

Lawson, T., Kroon, F., Russell, J., & Thuesen, P. (2010). *Audit and Prioritisation of Physical Barriers to Fish Passage in the Wet Tropics Region.* CSIRO Sustainable Ecosystems, Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.670.2304&rep=rep1&type=pdf

Barriers to fish passage, such as such as flood mitigation, drainage structures, and extensive road, rail and canerail networks, can have a significant impact on native fish assemblages. We identified artificial physical barriers in the Wet Tropics bioregion, Far North Queensland, Australia, through a desktop GIS analysis of the stream/river and transport networks. A total of 5,536 potential artificial, physical barriers to fish passage were identified in a stream network of 19,764 km at a scale of 1: 100 000. The Mulgrave (1,076) and Johnstone (1,069) basins contained the highest number of potential barriers, whilst most potential barriers comprised road crossings (66%) and cane rail crossings (18%). Due to the unavailability of consistent datasets at smaller scales, we have not identified artificial physical barriers smaller than 50 m. Hence it is very likely that the total number of potential barriers to fish passage in the region is many times higher. We subsequently prioritised the 5,536 potential barriers, to identify those barriers that will provide the greatest habitat value for native fish species when removed and/or mitigated. A total of 104 potential barriers were identified as high priority for rehabilitation, with the Daintree (32), Mossman (19) and Mulgrave (17) basins having the highest numbers. We recommend that the high priority status and attributes of these 104 barriers be verified on-ground, and that rehabilitation of barriers be experimentally examined as a management strategy to improve native fish movement and reduce invasive fish abundance in the Wet Tropics region.

O'Connor, J., Amtstaetter, F., Jones, M., & Mahoney, J. (2015). Prioritising the Rehabilitation of Fish Passage in a Regulated River System Based on Fish Movement. *Ecological Management & Restoration,* 16(1), 67-72. https://doi.org/10.1111/emr.12140

Environmental rehabilitation budgets are often limited, and management actions need to be prioritised to achieve the best outcomes. Prioritisation can best be done when evidence informs the decision-making process. We acoustically tagged twenty Golden Perch (Macquaria ambigua) in the Loddon River, Australia, and tracked their movements to gain an understanding on the requirements for fish passage at a major regulating structure, the Box Creek regulator. The movements of these fish were monitored through a network of receivers located throughout the lower Loddon River and Pyramid Creek system. Five fish moved 50-120km upstream, four of which reached the Box Creek regulator before moving back downstream to the entrance of the Kerang Lakes system. Most long distance upstream movements were associated with an increase in river discharge. The remaining 15 fish moved <20km, with all fish being detected at least once. This pilot study indicates that Box Creek regulator is acting as a barrier for some fish within the Loddon River system. Movement data also indicate that Golden Perch migration pathways may be influenced by river discharge. The management implications of this work includes the need to reinstate fish passage at Box Creek regulator and the potential use of environmental flows to enhance colonisation of native fish species throughout the Murray Darling Basin.

Salgado-Rojas, J., Alvarez-Miranda, E., Hermoso, V., Garcia-Gonzalo, J., & Weintraub, A. (2020). A Mixed Integer Programming Approach for Multi-Action Planning for Threat Management. *Ecological Modelling,* 418, 11. https://doi.org/10.1016/j.ecolmodel.2019.108901

Planning for management actions that address threats to biodiversity is important for securing its long term persistence. However, systematic conservation planning (SCP) has traditionally overlooked this aspect and just focused on identifying priority areas without any recommendation on actions needed. This paper develops a mixed integer mathematical programming (MIP) approach for the multi-action management planning problem (MAMP), where the goal is to find an optimal combination of management actions that abate threats, in an efficient way while accounting for connectivity. An extended version of the MAMP model (MAMP-E) is also proposed that adds an expression for minimizing fragmentation between different actions. To evaluate the efficiency of the two models, they were applied to a case study corresponding to a large area of the Mitchell River in Northern Australia, where 45 species of freshwater fish are exposed to the presence of four threats. The evaluation compares our exact MIP approach with the conservation planning software Marxan and the heuristic approach developed in Cattarino et al. (2015). The results obtained show that our MIP models have three advantages over their heuristic counterparts: shorter execution times, higher solutions quality, and a solution quality guarantee. Hence, the proposed MIP methodology provides a more effective framework for addressing the multi-action conservation problem.

Western North America

Al-Chokhachy, R., Shepard, B. B., Burckhardt, J. C., Garren, D., Opitz, S., Koel, T. M., . . . Gresswell, R. E. (2018). A Portfolio Framework for Prioritizing Conservation Efforts for Yellowstone Cutthroat Trout Populations. *Fisheries,* 43(10), 485-496. https://doi.org/10.1002/fsh.10137

Managing and conserving native taxa are becoming increasingly challenging because of mounting threats and limited resources, predicating the need for frameworks to prioritize conservation actions. We integrated attributes of population persistence, genetic status, threats from nonnative species, and threats from climatic shifts to prioritize conservation actions for Yellowstone Cutthroat Trout Oncorhynchus clarkii bouvieri. We used the individual attributes to rank populations and provide a framework for identifying the benefits of individual conservation actions. The majority of extant populations (57%) had a high probability (>0.75) of persistence, but nearly 70% of populations were either slightly hybridized or sympatric with nonnative species, and 44% of extant populations occupied habitat with low climatic resilience. Overall, we found that 36% of populations ranked as high (>0.75) conservation priority, and these populations primarily occupied large, relatively high-elevation habitats. The prioritization framework provides a platform for identifying and ranking actions with the greatest conservation effectiveness.

California Department of Fish and Wildlife. (2018). *Fish Passage Priorities - CDFW - 2018*. Retrieved from https://data.ca.gov/dataset/fish-passage-priorities-cdfw-2018-ds2817

Man-made barriers to salmonid migration include road /stream crossings, irrigation diversions and dams. Road /stream crossings are extremely numerous and often cross multiple road ownerships within a watershed. Passage impediments and delays in migration affect both adult and juvenile fish. Given the

magnitude and severity of the problem, reconnecting isolated stream habitat has become an important priority for the restoration of impaired anadromous salmon and steelhead stocks. A comprehensive CDFW fish passage program is vital towards identifying, prioritizing, and treating migration barriers so that unimpeded migration of California's salmonid populations is achieved. By coordinating resources with CDFW fisheries engineers, the Fisheries Restoration Grant Program and in conjunction with the Fish Passage Forum, a comprehensive program will aid in the recovery and de-listing of salmon and steelhead, in California. In 2008, the California departments of Fish and Game (now California Department of Fish and Wildlife (CDFW)) and Transportation (Caltrans) met with staff from the Assembly committees on Natural Resources and Transportation to discuss joint agency collaboration on prioritizing and remediating fish barriers to salmon and steelhead migration. This was in response to Senate Bill 857 requiring the California Department of Transportation to complete an assessment of potential barriers to anadromous fish prior to commencing any project using State or Federal transportation funds. In addition to the expectation that both agencies would develop a mutual list of priority barriers occurring along transportation corridors, a request was made to CDFW to provide a statewide list of priority barriers based on significance to fish migration and independent of who manages or is responsible for the stream crossing. CDFW developed its first list in 2011 and the point features mapped in this dataset represent the barrier locations from this list. CDFW has a more comprehensive list of barriers to salmon and steelhead migration; these barriers represent our effort to demonstrate and emphasize barrier priorities across both Coastal and Central Valley watercourses. As such, this spatial dataset presents the top priorities in each twenty-four Coastal and Central Valley counties for fish passage improvement. This list is a result of compilation and review by CDFW Regional biologists and supervisors (Regions 1-5) and by the Fisheries Branch. The prioritization process considered the following criteria: 1) high likelihood to improve migration for anadromous species; 2) availability of recent data of fish and habitat; 3) willing partners and land access; 4) known political support at a local, State or national level; 5) the site is a barrier to a federal recovery plan "Core" population; 6) the watercourse is an eco-regional significant watershed; 7) CDFW is committed to monitoring before, during and after any barrier improvement project is undertaken; and 8) the site is considered to be a "keystone barrier", meaning the barrier was the lower-most in that river or creek.

City of Bellingham Public Works Department. (2019). *2019 City of Bellingham Fish Barrier Prioritization Update*. Retrieved from https://cob.org/wp-content/uploads/2019-fish-barrier-prioritization.pdf

The City of Bellingham encompasses eight watershed and their associated streams (Figure 1). Most stream reaches are fish-bearing and support populations of both anadromous and resident salmon and trout. As documented in the City's Comprehensive Plan, the City is committed to stewarding fish and wildlife habitat, including fish-bearing streams. As part of this commitment, the City has a long history of improving fish passage throughout the City and Urban Growth Area both with independent restoration projects and in conjunction with other capital improvement projects. The City has developed and used prioritization tools to plan for these fish passage improvement projects.

Clearway Environmental. (2016). *Culvert Assessment and Fish Passage Prioritization Report for the Lower Nehalem Watershed.* Lower Nehalem Watershed Council. Retrieved from https://lnwc.nehalem.org/wp-content/uploads/2017/01/LNW_Culvert_Assessment_Prioritization_Report_FINAL.pdf

This report supplements existing data regarding culverts in the Lower Nehalem, and provides a comprehensive, up-to-date watershed scale assessment, with culverts ranked and prioritized for replacement. This prioritized list will be used to inform private landowners; federal, state, and local government agencies; and non-governmental organizations in order to focus efforts to systematically implement projects in high priority locations. In the past, the Lower Nehalem Watershed Council (LNWC) and their partners have completed on-the-ground restoration of crossings and upgraded culverts on a mostly opportunistic basis. Projects were identified mainly due to transportation safety, in conjunction with other restoration activities, and as brought before the Council by partners or landowners. While these projects have been highly successful in addressing fish passage barriers and have restored miles of stream habitat, this prioritized ranking of culverts will allow partners to plan and implement projects in a more systematic and effective way.

Copper River Watershed Project. (2011). *Prioritizing Fish Passage Improvement Projects in the Copper River Watershed.* Retrieved from https://copperriver.org/wp-content/uploads/2016/03/CRWPCulvertPrioritization.pdf

The Copper River Watershed Project (CRWP) and partners recognize that access to spawning and rearing habitats for salmonids are important factors for maintaining fish productivity in the Pacific Northwest, but culvert replacement projects are very expensive and the ecological benefits can vary greatly from one creek to the next. To help prioritize how to spend limited fish habitat restoration funds, CRWP has developed a protocol that assigns numerical value to ecological condition variables (i.e. fish presence/absence and quantity/quality of fish habitat) associated with road crossings and to culvert conditions. This scoring system will generate a number score for each culvert, providing an objective prioritization of potential fish passage improvement projects that make the best of available resources while maximizing ecological benefits to the aquatic system.

Greater Yamhill Watershed Council. (2012). *Yamhill Watershed Culvert Prioritization and Action Plan for Fish Passage.* National Fish and Wildlife Foundation, U.S. Bureau of Land Management, & Confederated Tribes of Grand Ronde. Retrieved from http://www.gywc.org/sites/default/files/Documents/Yamhill%20Culvert%20Prioritization%20Report.pdf

From 2003 - 2012, the BLM, in collaboration with the Confederated Tribes of Grand Ronde and the Greater Yamhill Watershed Council, conducted an inventory of the culverts acting as fish passage barriers in select areas within the Yamhill watershed. Three subwatersheds were studied: Mill Creek, North Yamhill River, and Willamina Creek. Approximately 2056 modeled stream crossings were assessed, of which 178 culverts were surveyed and prioritized as barriers to migratory fish species. A local stakeholder group guided the prioritization process and reviewed the prioritization results. This project has identified seven high priority culverts, fifteen medium, and one hundred fifty-six low. Where appropriate, the high and medium priority culverts were grouped together to facilitate project

development and funding efficiencies. Collectively, replacing all the high and medium ranked culverts in this Plan would improve access to an estimated 78.7 miles of habitat across the Mill Creek, North Yamhill River, and Willamina Creek watersheds.

Ioannidou, C., & O'Hanley, J. R. (2019). The Importance of Spatiotemporal Fish Population Dynamics in Barrier Mitigation Planning. *Biological Conservation,* 231, 67-76. https://doi.org/10.1016/j.biocon.2019.01.001

In this study, we propose a novel framework combining spatially explicit population viability analysis and optimization for prioritizing fish passage barrier mitigation decisions. Our model aims to maximize the equilibrium population size, or alternatively minimize the extinction risk, of a target fish species subject to a budget on the total cost of barrier mitigation. A case study involving a wild coho salmon (Oncorhynchus kisutch) population from the Tillamook basin, Oregon, USA is used to illustrate the benefits of our approach. We consider two different spawning adult dispersal patterns, river and reach level homing, as well as straying. Under density dependent population growth, we find that homing behavior type has a significant effect on barrier mitigation decisions. In particular, with reach homing, our model produces virtually the same population sizes as a more traditional barrier prioritization procedure designed to maximize accessible habitat. With river homing, however, we find that it is not necessary to remove all barriers in order to maximize equilibrium population size. Indeed, a stochastic version of our model reveals that removing all barriers actually results in a marginal increase in quasi-extinction risk. We hypothesize that this is due to a population thinning effect of barriers, resulting in a surplus of recruits in areas of low spawner density. Our findings highlights the importance of considering spatiotemporal fish population dynamics in river connectivity restoration planning. By adding greater biological realism, models such as ours can help conservation managers to more strategically allocate limited resources, resulting in both cost savings and improved population status for a focal species.

Kraft, M., Rosenberg, D. E., & Null, S. E. (2019). Prioritizing Stream Barrier Removal to Maximize Connected Aquatic Habitat and Minimize Water Scarcity. *Journal of the American Water Resources Association,* 55(2), 382-400. https://doi.org/10.1111/1752-1688.12718

Instream barriers, such as dams, culverts, and diversions, alter hydrologic processes and aquatic habitat. Removing uneconomical and aging instream barriers is increasingly used for river restoration. Historically, selection of barrier removal projects used score-and-rank techniques, ignoring cumulative change and the spatial structure of stream networks. Likewise, most water supply models prioritize either human water uses or aquatic habitat, failing to incorporate both human and environmental water use benefits. Here, a dual-objective optimization model identifies barriers to remove that maximize connected aquatic habitat and minimize water scarcity. Aquatic habitat is measured using monthly average streamflow, temperature, channel gradient, and geomorphic condition as indicators of aquatic habitat suitability. Water scarcity costs are minimized using economic penalty functions while a budget constraint specifies the money available to remove barriers. We demonstrate the approach using a case study in Utah's Weber Basin to prioritize removal of instream barriers for Bonneville cutthroat trout, while maintaining human water uses. Removing 54 instream barriers reconnects about 160 km of quality-weighted habitat and costs approximately US$10 M. After this point, the cost-effectiveness of

removing barriers to connect river habitat decreases. The modeling approach expands barrier removal optimization methods by explicitly including both economic and environmental water uses.

Kuby, M. J., Fagan, W. F., ReVelle, C. S., & Graf, W. L. (2005). A Multiobjective Optimization Model for Dam Removal: An Example Trading Off Salmon Passage with Hydropower and Water Storage in the Willamette Basin. *Advances in Water Resources,* 28(8), 845-855. https://doi.org/10.1016/j.advwatres.2004.12.015

We introduce the use of systematic, combinatorial, multiobjective optimization models to analyse ecological-economic tradeoffs and to support complex decision-making associated with dam removal in a river system. The model's ecological objective enhances salmonid migration and spawning by maximizing drainage area reconnected to the sea. The economic objective minimizes loss of hydropower and storage capacity. We present a proof-of-concept demonstration for the Willamette River watershed (Oregon, USA). The case study shows a dramatic tradeoff in which removing twelve dams reconnects 52% of the basin while sacrificing only 1.6% of hydropower and water-storage capacity. Additional ecological gains, however, come with increasingly steeper economic costs. A second model incorporates existing fish-passage systems. Because of data limitations and model simplifications, these results are intended solely for the purpose of illustrating a novel application of multiobjective programming to dam-removal issues. Far more work would be needed to make policy-relevant recommendations. Nevertheless, this research suggests that the current practice of analysing dam-removal decisions on a dam-by-dam, basis be supplemented by evaluation on a river-system basis, trading off economic and ecological goals.

Loffink, K., & Apke, G. (2013). *Concurrent Sessions C: Prioritization - Oregon Fish Passage Priority List - a Statewide Barrier Prioritization Effort*. Paper presented at the International Conference on Engineering and Ecohydrology for Fish Passage. https://scholarworks.umass.edu/fishpassage_conference/2013/June26/72/?utm_source=scholarworks.umass.edu%2Ffishpassage_conference%2F2013%2FJune26%2F72&utm_medium=PDF&utm_campaign=PDFCoverPages

Fish passage is a key component to many facets of fisheries resource management. Connectivity between aquatic habitats is an important part of garnering successful and healthy fish populations. Without habitat connectivity, resident or fluvial fish species such as native trout and suckers become isolated, leading to reduced levels of genetic diversity and fitness. For anadromous populations, fish passage can allow access to new habitats or fertile spawning grounds that are pivotal for success of the species. In addition to providing access to vital spawning habitats for adults, fish passage also provides access to essential rearing habitats for juvenile life histories. Population isolation due to fish passage barriers also heightens migratory fish exposure to disturbances, thus increasing the potential magnitude of the disturbance at a population level. Fish passage barriers are prevalent throughout the Oregon landscape. Over time, despite fish passage rules and regulations, access to native fish habitats has been blocked or impaired by the construction of impassable culverts, dams, tide gates, dikes, bridges, and other anthropogenic infrastructure. Providing passage at these artificial obstructions is vital to recovering Oregon’s native migratory fish populations. The Oregon Department of Fish and Wildlife’s (ODFW) latest inventory shows over 27,800 artificial obstructions to fish passage in the State of Oregon.

Of those, only 17% are documented as providing adequate fish passage for native migratory fish. With so many barriers spread across the landscape, and funding becoming scarce, it is paramount that we thoroughly prioritize fish passage, with inclusion of multiple parameters. This will allow for a focused effort to improving passage conditions and meeting a critical need of Oregon's native migratory fish. This presentation will focus on the development and methodology used to prioritize fish passage barriers across the State of Oregon.

Maitland, B. M., Poesch, M., & Anderson, A. E. (2016). Prioritising Culvert Removals to Restore Habitat for at-Risk Salmonids in the Boreal Forest. *Fisheries Management and Ecology,* 23(6), 489-502. https://doi.org/10.1111/fme.12188

In the boreal forests of Canada, industrial development has resulted in the installation of thousands of culverted road crossings that act as barriers to fish movement and degrade habitat for native freshwater fishes. In view of culvert removals being expensive, prioritisation methods have been developed, but the efficacy of such methods has not been thoroughly investigated nor have they been tested on low-gradient boreal forest watersheds containing at-risk salmonids. The management utility of a novel GIS-based optimisation-planning tool to prioritise fish barrier remediation was tested in two highly developed watersheds. Region-specific parameter estimates of monetary variables (e.g. budget, individual barrier remediation costs), barrier passability and biologically relevant information for species on conservation concern (e.g. habitat suitability, dispersal ability) were incorporated. Results indicate that for Arctic grayling, Thymallus arcticus Pallas, and bull trout, Salvelinus confluentus Suckley, a large proportion (similar to 61-83%) of currently isolated habitat can be reconnected with low investment (similar to$200-$500 K). This study demonstrates the management utility of barrier optimisation methods for use in boreal watersheds, particularly as it significantly reduces the technical expertise needed to perform relatively complex optimisation analyses.

Null, S. E., Medellin-Azuara, J., Escriva-Bou, A., Lent, M., & Lund, J. R. (2014). Optimizing the Dammed: Water Supply Losses and Fish Habitat Gains from Dam Removal in California. *Journal of Environmental Management,* 136, 121-131. https://doi.org/10.1016/j.jenvman.2014.01.024

Dams provide water supply, flood protection, and hydropower generation benefits, but also harm native species by altering the natural flow regime and degrading aquatic and riparian habitat. Restoring some rivers reaches to free-flowing conditions may restore substantial environmental benefits, but at some economic cost. This study uses a systems analysis approach to preliminarily evaluate removing rim dams in California's Central Valley to highlight promising habitat and unpromising economic use tradeoffs for water supply and hydropower. CALVIN, an economic-engineering optimization model, is used to evaluate water storage and scarcity from removing dams. A warm and dry climate model for a 30-year period centered at 2085, and a population growth scenario for year 2050 water demands represent future conditions. Tradeoffs between hydropower generation and water scarcity to urban, agricultural, and instream flow requirements were compared with additional river kilometers of habitat accessible to anadromous fish species following dam removal. Results show that existing infrastructure is most beneficial if operated as a system (ignoring many current institutional constraints). Removing all rim dams is not beneficial for California, but a subset of existing dams are potentially promising candidates for removal from an optimized water supply and free-flowing river perspective. Removing individual

dams decreases statewide delivered water by 0-2282 million cubic meters and provides access to 0 to 3200 km of salmonid habitat upstream of dams. The method described here can help prioritize dam removal, although more detailed, project-specific studies also are needed. Similarly, improving environmental protection can come at substantially lower economic cost, when evaluated and operated as a system.

O'Hanley, J. R., & Tomberlin, D. (2005). Optimizing the Removal of Small Fish Passage Barriers. *Environmental Modeling & Assessment,* 10(2), 85-98. https://doi.org/10.1007/s10666-004-4268-y

Removing small artificial barriers that hinder upstream migrations of fish is a major problem in riparian habitat restoration. Because of budgetary limitations, it is necessary to prioritize barrier removal and repair decisions. These have usually been based on scoring and ranking procedures, which, although simple to use, can be very inefficient in terms of increasing the amount of accessible instream habitat. We develop a novel decision-making approach, based on integer programming techniques, which optimizes repair and removal decisions. Results show based on real datasets of barrier culverts located in Washington State that scoring and ranking is over 25% below the optimum on average and a full 100% below in the worst case, producing no net habitat gain whatsoever. This is compared to a dynamic programming method that was able to find optimal solutions in less than a second, even for problems with up to several hundred variables, and a heuristic method, which found solutions with less than a 1% average optimality gap in even less time.

Oregon Department of Fish and Wildlife. (2019). *2019 Statewide Fish Passage Priority List*. Retrieved from https://www.dfw.state.or.us/fish/passage/docs/2019%20Fish%20Passage%20Prioritization%20Methods%20Paper.pdf

Populations of migratory fish are dependent on their ability to access quality habitat in order to complete important ecological life history strategies. In Oregon, this often means migratory fish must travel extensive distances through various habitats to complete these life histories. Unfortunately, their passage is often blocked by man-made (anthropogenic) features which act as barriers to fish movement, defined in Oregon Revised Statutes (ORS) 509.580 (1) as Artificial Obstructions. There are currently 42,780 inventoried artificial barriers in Oregon that can potentially inhibit fish movement. Due to the volume of these barriers and the associated cost of repairing them, only a small proportion receive attention each year. Oregon Department of Fish and Wildlife (ODFW) has constructed a prioritization list of 591 barriers (Appendix A) to identify barriers that maximize the return of native migratory fish to critical habitats. Scoring criteria are calculated to estimate the amount of habitat gained for purposes of prioritizing artificial obstructions at which fish passage would benefit native migratory fish in the State of Oregon.

Sethi, S. A., O'Hanley, J. R., Gerken, J., Ashline, J., & Bradley, C. (2017). High Value of Ecological Information for River Connectivity Restoration. *Landscape Ecology,* 32(12), 2327-2336. https://doi.org/10.1007/s10980-017-0571-2

Efficient restoration of longitudinal river connectivity relies on barrier mitigation prioritization tools that incorporate stream network spatial structure to maximize ecological benefits given limited resources. Typically, ecological benefits of barrier mitigation are measured using proxies such as the amount of accessible riverine habitat. We developed an optimization approach for barrier mitigation planning which directly incorporates the ecology of managed taxa, and applied it to an urbanizing salmon-bearing watershed in Alaska. A novel river connectivity metric that exploits information on the distribution and movement of managed taxon was embedded into a barrier prioritization framework to identify optimal mitigation actions given limited restoration budgets. The value of ecological information on managed taxa was estimated by comparing costs to achieve restoration targets across alternative barrier prioritization approaches. Barrier mitigation solutions informed by life history information outperformed those using only river connectivity proxies, demonstrating high value of ecological information for watershed restoration. In our study area, information on salmon ecology was typically valued at 0.8-1.2 M USD in costs savings to achieve a given benefit level relative to solutions derived only from stream network information, equating to 16-28% of the restoration budget. Investing in ecological studies may achieve win-win outcomes of improved understanding of aquatic ecology and greater watershed restoration efficiency.

The Watershed Company. (2014). *Skagit County High Priority Culvert Replacements for Fish Passage.* Skagit County Public Works. Retrieved from https://www.skagitcounty.net/PublicWorksNaturalResourcesManagement/Documents/High%20Priority%20Culvert%20Replacements%20for%20Fish%20Passage.pdf

The Watershed Company (TWC) is assisting Skagit County with evaluation, prioritization, and conceptual design of culvert replacement projects to improve fish passage. This report includes the identification and assessment of ten culverts at County road crossings that currently limit fish passage.

U.S. Fish and Wildlife Service. (2016). *Salmon Passage Restoration Cost-Benefit Prioritization for the Matanuska-Susitna Basin, Alaska*. (Alaska Fisheries Technical Report Number 108). Retrieved from https://www.arlis.org/docs/vol1/F/FishPassage/Dekker-2016.pdf

The Matanuska-Susitna (Mat-Su) basin in Southcentral Alaska is home to five species of Pacific salmon (Oncorhynchus spp.) and is the fastest developing region in Alaska. Since 2000, the Alaska Department of Fish and Game (ADF&G) has documented a total of 573 manmade stream crossings, typically culverts at stream crossings in the Mat-Su. This is estimated to be over 95% of all Mat-Su crossings in fish-bearing waters. The U.S. Fish and Wildlife Service (USFWS), ADF&G and the Mat-Su Basin Salmon Habitat Partnership (Partnership) have worked since 2000 to restore fish passage at sites that do not provide adequate salmon passage. To optimize barrier replacement efforts the Partnership identified the need for a cost-benefit prioritization of salmon barriers at road-stream crossings. This was done by developing a barrier replacement cost estimate and measuring the length of habitat upstream of each barrier. From measurements of distance upstream of each barrier and an estimated cost based on a nonlinear regression of past replacement costs and stream width, we calculated an estimated

replacement cost per mile. Top barriers were selected based on miles of upstream habitat and then ranked by their cost-benefit value. Barriers replaced for salmon passage were also identified because no comprehensive list existed since replacement projects began in 2000 and an analysis of past replacements was used to inform this report. As of 2015, 476 of the 573 inventoried fish passage sites were located on salmon bearing streams, and 287 were classified by ADF&G as likely or potential passage barriers for 55 mm juvenile Coho Salmon O. kisutch. These barriers may affect juvenile salmon access to an estimated 455 miles of habitat. Of the 287 classified barriers, 55 accounted for 75% of the total miles of habitat upstream of barriers and were selected for the cost-benefit analysis. Results of the cost-benefit analysis indicate that 15 of the 55 barriers with the lowest cost per mile value should be given priority for restoration over the next 5 years. The 15 barriers selected account for 184.5 miles and would cost approximately $4.8 million to replace. Future prioritizations could include additional factors such as upstream habitat quality, lake acreage, culvert perch height, improved stream network miles, improved cost estimates, presence of invasive Northern Pike (Esox Lucius) or Partnership-defined priority water bodies.

Upper Columbia Salmon Recovery Board, & Aspect Consulting Inc. (2018). *Fish Passage Project Prioritization in the Upper Columbia.* Retrieved from http://www.ucsrb.org/?mdocs-file=3160

Prioritization is a critical component of the Regional Technical Team's (RTT's) Biological Strategy to Protect and Restore Salmonid Habitat in the Upper Columbia Region, which was last updated in 2017. The objective of the Fish Passage Prioritization Strategy is to provide a consistent, repeatable, systematic, and well-documented approach for prioritizing fish passage projects. This intent is to provide a transparent prioritization process that will assist restoration practitioners and managers with making decisions. We will revise this strategy periodically as new information becomes available or the need for revisions arises. Because the prioritization strategy has been built by Aspect Consulting, Inc. into an ArcGIS tool, changes can be made to the underlying metrics, weightings, or scoring systems and the tool can be rerun with new barrier datasets at any time.

Washington Department of Fish and Wildlife. (2019). *Fish Passage Inventory, Assessment, and Prioritization Manual*. Retrieved from https://wdfw.wa.gov/publications/02061

The Fish Passage Inventory, Assessment, and Prioritization Manual provides standardized guidance for assessing structures that potentially block adult salmonid passage, and identifying surface water diversion deficiencies. It also provides an established protocol for prioritizing barrier corrections. These protocols are widely utilized and accepted, and provide a consistent approach to evaluating fish passage barriers statewide.

Eastern North America

Hoenke, K. M., Kumar, M., & Batt, L. (2014). A Gis Based Approach for Prioritizing Dams for Potential Removal. *Ecological Engineering,* 64, 27-36. https://doi.org/10.1016/j.ecoleng.2013.12.009

Dam removal has proven to be an effective mechanism for quickly restoring in-stream habitat and returning stream systems to a free flowing state in a wide range of settings. Identification of dam removal projects can be a tedious task that often accounts for multiple social, ecological and hydrologic criteria. Here, a GIS based approach for prioritizing dams for removal based on eco-hydrologic and social metrics is presented. The tool uses a hierarchical decision-support framework to rank dams for removal based on criteria such as good habitat and water quality connectivity, larger streamflow at the dam, improved dam safety and longer stream mile connectivity. The tool is applied for three commonly considered prioritization scenarios that rank dams based on their suitability for removal using: ecological criteria, both social and ecological criteria together, and habitability of anadromous fish criteria. Results show that highest ranking dams from an ecological prioritization are located on reaches of high habitat quality and longer connected river miles. In contrast, social plus ecological prioritization yields higher ranks to dams that are primarily used for recreation, but are also in areas of high habitat quality. Dams in close proximity to anadromous fish spawning areas with high river mileage and few downstream dams are ranked higher by anadromous fish prioritization. Notably, some dams rank high in all criteria. These dams should be paid particular attention to, as they could potentially provide the best benefit if removal is possible. The top 20 ranked dams, as predicted by the tool, includes dams that had been pre-identified by resource managers as potential dam removal projects, indicating that the tool is performing as intended. The tool and presented results should be used as a screening tool in conjunction with the expert knowledge of resource managers to further investigate the influence of site-specific factors, thereby determining the final priority of projects.

King, S., & O'Hanley, J. R. (2016). Optimal Fish Passage Barrier Removal Revisited. *River Research and Applications,* 32(3), 418-428. https://doi.org/10.1002/rra.2859

Infrastructure, such as dams, weirs and culverts, disrupt the longitudinal connectivity of rivers, causing adverse impacts on fish and other aquatic species. Improving fish passage at artificial barriers, accordingly, can be an especially effective and economical river restoration option. In this article, we propose a novel, mixed integer programing model for optimizing barrier mitigation decisions given a limited budget. Rather than simply treating barriers as being impassable or not, we consider the more general case in which barriers may be partially passable. Although this assumption normally introduces nonlinearity into the problem, we manage to formulate a linear model via the use of probability chains, a newly proposed technique from the operations research literature. Our model is noteworthy in that it can be readily implemented and solved using off-the-shelf optimization modelling software. Using a case study from the US State of Maine, we demonstrate that the model is highly efficient in comparison with existing solution methods and, moreover, highly scalable in that large problems with many thousands of barriers can still be solved optimally. Our analysis confirms that barrier mitigation can provide substantial ecological gains for migratory fish at low levels of investment.

Martin, E. H. (2019). Assessing and Prioritizing Barriers to Aquatic Connectivity in the Eastern United States. *JAWRA Journal of the American Water Resources Association,* 55(2), 401-412. https://doi.org/10.1111/1752-1688.12694

There are tens of thousands of dams and millions of road-stream crossings in the eastern United States (U.S.) which can prevent fish and other aquatic organisms from accessing key habitats. There is growing momentum in the eastern U.S., and throughout the country, to remove dams which no longer serve their intended purpose, provide improved fish passage facilities at those dams that cannot feasibly be removed, and upgrade road-stream crossings to benefit aquatic organism passage (AOP). However, these projects are expensive and given the extensive scope of the problem and the limited resources available to address it, it is imperative to be strategic in deciding which barriers are removed or upgraded. The Nature Conservancy, in conjunction with several partners, has conducted a suite of analyses which assess and prioritize barriers to AOP for the potential ecological gains that could be realized if they were removed or upgraded. The results of these analyses have been used both proactively and reactively by managers throughout the eastern U.S. to identify potential connectivity restoration projects, support funding requests, and help inform funding allocation decisions by providing a common evaluation system for the many thousands of potential projects. In contrast to more prescriptive barrier removal optimizations, their flexibility of use provides managers with a practical framework for planning aquatic connectivity restoration while remaining open to the element of opportunity.

McKay, S. K., Batt, L., Bringolf, R. B., Davie, S., Elkins, D. C., & Hoenke, K. M. (2013). *Fish Passage in Georgia: Planning for the Future.* Paper presented at the 2013 Georgia Water Resources Conference. Retrieved from https://smartech.gatech.edu/bitstream/handle/1853/48504/3.2.1_McKay.pdf

In 14 major watersheds and thousands of miles of rivers, Georgia's waterways provide some of the highest levels of aquatic biodiversity in the United States. Hydrologic disconnection by dams, roads, water diversions, and other barriers have led to local declines in both migratory and resident fishes. To counteract these trends, numerous organizations and stakeholders have invested in fish passage structures and dam removal. Techniques for prioritizing barrier improvement, measuring passage efficacy, and designing passage structures are rapidly developing in both research and practice. We review the status of fish passage improvement in the state of Georgia as it relates to two key topics. First, what methods exist (or are being developed) to prioritize barrier improvement? Second, what lessons have been learned from recent fish passage and dam removal projects? We address these questions by way of example projects conducted by a variety of agencies and entities. We conclude by summarizing some emerging challenges and opportunities for future research in fish passage improvement.

McKay, S. K., Reif, M. K., Conyngham, J., & Kohtio, D. M. (2017). *Barrier Prioritization in the Tributaries of the Hudson-Raritan Estuary*. (ERDC/TN EMRRP-SR-82). https://doi.org/10.21079/11681/25911

The Hudson-Raritan Estuary (HRE) Ecosystem Restoration Feasibility Study is a large multi-objective, watershed-scale ecosystem restoration initiative led by the U.S. Army Corps of Engineers (USACE) New York District in cooperation with its non-federal sponsors (Port Authority of New York and New Jersey,

State of New Jersey, New York City Department of Environmental Protection, and Westchester County Department of Planning). One study outcome was the development of a Comprehensive Restoration Plan (CRP) that serves as a master plan and blueprint for future restoration in the HRE. The CRP's goal is to develop a mosaic of habitats that provide the public with renewed and increased benefits from the estuary. In addition, the CRP provides the framework for an estuary-wide ecological restoration program by utilizing restoration targets –Target Ecosystem Characteristics (TECs) – developed by the region's stakeholders. One TEC focuses on restoring tributary environments and reconnecting rivers to coastal environments that benefit impacted or imperiled migratory fishes (e.g., Alewife, blueback herring, Striped bass, American shad, and American eel). This technical note describes a procedure developed to prioritize removal of major migratory barriers, specifically dams. These methods are demonstrated in one of eight planning regions, the Harlem River, East River, and Western Long Island Sound Planning Region, where they were applied to prioritize potential barriers for removal over a range of costs. The prioritization scheme is based on four primary components: habitat quantity upstream of a dam, habitat quality upstream of a dam, the effects of multiple dams in sequence in the context of diadromous fish (i.e., if a fish cannot pass the most downstream dam, then upstream dam removal provides no benefits), and a rapid, screening-level relative cost estimate. This technique is then applied to examine 49 potential dam removal sites. A combinatorial algorithm was applied to develop plans with more than 489,000 combinations of removal sites (e.g., remove barrier-A, barrier-B, neither, or both). From this analysis, 49 proposed sites were screened and refined to a recommended plan containing 12 sites, which provides 66% of the total potential habitat gain at 19% of the relative cost. The advantages and challenges of barrier prioritization are then discussed more broadly with an emphasis on efficiencies that can arise as a result of spatial prioritization methods.

McManamay, R. A., Perkin, J. S., & Jager, H. I. (2019). Commonalities in Stream Connectivity Restoration Alternatives: An Attempt to Simplify Barrier Removal Optimization. *Ecosphere,* 10(2). https://doi.org/10.1002/ecs2.2596

Movement within stream corridors is a basic life history requirement of many aquatic organisms. Barrier removal in streams has become a common practice in the United States aimed to restore organism dispersal and meet conservation objectives; however, there are social and economic costs to the removal of barriers. Accordingly, tools to prioritize barrier removal, particularly optimization techniques, can be used to evaluate cost-benefit trade-offs. Many of these techniques, however, require programming experience and are not available to natural resource managers. Furthermore, conservation objectives vary considerably depending on the life histories of organisms under consideration, and these opposing objectives, in conjunction with variant socioeconomic costs, will influence optimization solutions, specifically which barriers to remove. To promote the use of optimization tools, straightforward and open-access platforms are needed to support use by managers, while also providing general approaches for holistic basin-scale connectivity restoration. Herein, we use two case studies, White Oak Creek (small watershed) and the Roanoke River Basin (large basin), to explore the divergent outcomes stemming from different conservation objectives and socioeconomic costs used to prioritize barrier removal. We conducted optimization modeling using a widely accessible platform along with an open-access solver plug-in to support a wide variety of conservation objectives. We used simple approaches to find commonalities in barriers identified for removal among divergent conservation objectives and provide alternative (i.e., hybrid removal-passage) strategies for approaching habitat restoration for diverse aquatic communities while increasing social benefits (i.e., hydropower energy). As expected, different conservation objectives aimed to support varied species life histories

(e.g., diadromy, large-river vs. small-river potamodromy) have very different effects on optimization solutions. In both case studies, however, commonalities in solutions were identified through clustering groups of barriers into general connectivity restoration strategies. Furthermore, strategy types for a given barrier could be predicted with >= 72% accuracy using only four metrics. This suggests that optimization results can be simplified into general standards to support adoption of sustainable basin connectivity criteria strategies. Our framework provides a flexible and open-access approach to conduct relatively complex optimization modeling for stream barrier prioritization, while examining potential for agreement among divergence conservation objectives.

Nathan, L. R., Welsh, A. B., & Vokoun, J. C. (2019). Watershed-Level Brook Trout Genetic Structuring: Evaluation and Application of Riverscape Genetics Models. *Freshwater Biology,* 64(3), 405-420. https://doi.org/10.1111/fwb.13230

Stream connectivity promotes resilience and population viability of aquatic organisms. Landscape genetic approaches, traditionally applied to terrestrial systems, may reveal important watershed-level dynamics that influence connectivity. Additional validation would improve understanding of how the models perform when gene flow is constrained to dendritic networks. The objectives of this study were to use simulations to assess the utility of landscape genetics analyses in dendritic stream networks and investigate riverscape variables influencing gene flow among brook trout Salvelinus fontinalis populations in headwater streams. We used an individual-based simulation program to simulate different dispersal scenarios and used combinations of landscape genetic models, model selection methods, and genetic metrics to determine the best combination for riverscape systems. We also sampled brook trout from 76 headwater streams in two watersheds (c. 1,000 km(2)) in Connecticut, U.S.A. to assess connectivity and riverscape influences on genetic structuring. Gravity models with Bayesian information criterion (BIC) selection were the most accurate (>85%) landscape genetic models that consistently identified the correct simulated gene flow barrier. However, all models performed poorly when unidirectional barriers were simulated without a distance-based dispersal limitation. Excluding this scenario, model accuracy for the gravity models using BIC selection was >90% across multiple genetic metrics, validating the application of landscape genetic models to riverscape systems. We found highly variable levels of brook trout genetic connectivity (F-ST range 0.01-0.19) at the watershed level (5-15 river km). Gravity models identified increases in upstream impervious surfaces and decreases in riparian tree canopy cover as riverscape variables associated with increases in genetic differentiation in one watershed, while the other watershed was consistent with an isolation by distance pattern. In this study we used demogenetic (i.e. combined demographic and genetic) simulations to demonstrate the utility of landscape genetics techniques in dendritic river networks. Our empirical genetic study documented gene flow among headwater populations of brook trout at the watershed level and also suggested connectivity can be limited by watershed development. Incorporating the heterogeneity of riverscapes into connectivity-focused conservation planning is essential to the development of effective restoration actions, and landscape genetics approaches can be useful tools to identify watershed-level connectivity in stream systems.

Smith, D. R., Butler, R. S., Jones, J. W., Gatenby, C. M., Hylton, R. E., Parkin, M. J., & Schulz, C. A. (2017). Developing a Landscape-Scale, Multi-Species, and Cost-Efficient Conservation Strategy for Imperilled Aquatic Species in the Upper Tennessee River Basin, USA. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 27(6), 1224-1239. https://doi.org/10.1002/aqc.2785

Strategic conservation of imperilled species faces several major challenges including uncertainty in species response to management actions, budgetary constraints that limit options, and the need to scale expected conservation benefits from local to landscape levels and from single to multiple species. A structured decision-making process was applied to address these challenges and identify a cost-effective conservation strategy for the Federally listed endangered and threatened aquatic species in the Upper Tennessee River Basin (UTRB). The UTRB, which encompasses a landscape of similar to 58 000 km(2), primarily in western North Carolina, eastern Tennessee, and south-western Virginia, harbours one of the most globally diverse assemblages of freshwater fishes and mussels at temperate latitudes. To develop a strategy for conservation of 12 fish species and 24 mussel species over a 20-year period, a management strategy that would best recover these species was identified given costs and uncertainty in management effectiveness. The main insights came from a trade-off analysis that compared alternative allocations of effort among management actions. A strategy emphasizing population management, which included propagation and translocation, performed best across a wide range of objective weightings and was robust to uncertainty in management effectiveness. Species prioritization was based on the expected conservation benefit from the best performing strategy, degree of imperilment, and species-specific management costs. Sub-basin prioritization was based on expected conservation benefit from the best performing strategy and feasibility of habitat management and threat abatement. Although the strategy was developed for imperilled aquatic species in the UTRB, the structured process is applicable for developing cost-efficient strategies to conserve multiple species across a landscape under uncertain management effectiveness. The process can assist a manager with limited resources to understand which species to work on, where to conduct that work, and what work would be most beneficial for those species in those catchments.

The Nature Conservancy. (2019). *Chesapeake Fish Passage Prioritization: An Assessment of Damns in the Chesapeake Bay Watershed*. Retrieved from https://cbtrust.org/wp-content/uploads/14587_Chesapeake-Fish-Passage.pdf

The Chesapeake Fish Passage Prioritization has been used since 2013 to help identify potential dam removals and fish passage projects, secure and allocate funds for these projects, and help to communicate the importance of aquatic connectivity in the Chesapeake Bay watershed. Starting in 2017, The Nature Conservancy began a revised version of this analysis. This revised report adds sections to address these changes (in particular Sections 6 and 7), modifies the original report elsewhere as needed (e.g. revised weights for the resident fish scenario in Table 4-3), while leaving other sections unaltered from the original 2013 version. For additional information on the approach used in this analysis, please refer to the peer reviewed journal article that covers this and its sibling projects: Assessing and Prioritizing Barriers to Aquatic Connectivity in the Eastern United States (Martin 2018).

Walter, T., DeGaetano, A., Meyer, A., & Marjerison, R. (2015). *Determining Peak Flow under Different Scenarios and Assessing Organism Passage Potential: Identifying and Prioritizing Undersized and Poorly Passable Culverts: Year 2.* New York State Water Resources Institute, Cornell University Ithaca, NY. Retrieved from https://wri.cals.cornell.edu/sites/wri.cals.cornell.edu/files/shared/2014-Walter-UndersizedCulverts-final-Feb2015.pdf

The continuing objective of this project was to identify undersized culverts, for both current and future precipitation conditions. Undersized culverts often present increased risks of wash-outs or overtopping during storms, which can present safety risks in communities and come with substantial costs. Having the information necessary to upsize culverts proactively can allow communities to improve their climate resilience. This year, we also looked at the potential for culverts to act as barriers to the unimpeded movement of aquatic and riparian organisms. Through field assessments and a scoring algorithm, road-stream crossings were rated for their passability to organisms. By giving communities the information required to prioritize their crossings for both capacity and passability, we can restore organisms' access to stream habitat while at the same time lower a municipality's longterm infrastructure costs by preparing for changing precipitation and flow regimes. The specific objectives were to determine the capacity of culverts within the study watersheds, calculate the peak storm discharge at each culvert for current and future precipitation conditions and compare runoff to capacity to identify culverts that are currently undersized, and those which are likely to be undersized in the future. The specific passability-related objectives were to rank each road-stream crossing for its passability by using the River and Stream Continuity Project's field protocol and existing database functions. This year we also analyzed several environmental and societal variables that might influence culvert suitability in a watershed or town. The online culvert-capacity calculator developed last year was expanded in response to feedback from users last year.

Great Lakes

Fitzpatrick, K. B., & Neeson, T. M. (2018). Aligning Dam Removals and Road Culvert Upgrades Boosts Conservation Return-on-Investment. *Ecological Modelling,* 368, 198-204. https://doi.org/10.1016/j.ecolmodel.2017.11.018

Dams and road culverts fragment river ecosystems worldwide by restricting the movement of aquatic species. In many watersheds, a diverse set of actors coordinates the removal of these barriers. Non-governmental organizations often focus on small dams and road culverts, while large dam removal projects are coordinated by federal agencies or coalitions of partners. Here we evaluate the return-on-investment of these strategies by exploring a continuum of methods for selecting barrier removal projects, ranging from a focus on many small barrier removal projects to a few large ones. We used estimated removal costs of more than 100,000 barriers in the North American Great Lakes to construct economically realistic barrier removal scenarios. We then simulated the movement of stream-resident and anadromous fishes through model river networks with a few large dam removals, many road culvert retrofits, or a mix of both. We found that the strategy of removing both dams and road culverts had the greatest potential to benefit both stream-resident and anadromous fishes, but only when projects were aligned longitudinally within the river network. Our results demonstrate the importance of allocating conservation resources to both small and large restoration projects, and highlight a need for increased coordination and communication among the many different organizations investing in barrier removals.

Our findings complement optimization approaches to prioritizing barrier removals by providing general guidelines for practitioners to follow when project selection must depart from a prescribed portfolio of projects.

Lin, H. Y., Robinson, K., Milt, A., & Walter, L. (2019). The Application of Decision Support Tools and the Influence of Local Data in Prioritizing Barrier Removal in Lower Michigan, USA. *Journal of Great Lakes Research,* 45(2), 360-370. https://doi.org/10.1016/j.jglr.2019.01.008

Web-based decision support tools (DSTs) can be useful to facilitate decision-making processes for managing complex natural resource systems. However, the alignment of DSTs with the objectives in governmental policies or management plans and the influence of limited local data on the outputs of these tools may reduce the use of DSTs by decision makers. In this study, we examined the outcomes of web-based DSTs when different types of local data were incorporated and demonstrated a way to incorporate outputs from multiple DSTs or local inventories to benefit barrier removal decisions. Restoring habitat connectivity in rivers in northwest lower Michigan, USA, was used as a case study due to the abundance of local inventory data and web-based DSTs. We found that, when compared to prioritizations made using local data, some DSTs could produce similar outcomes (in barriers selected, cost, and the benefit for migratory fish) with limited data, but the trade-offs among users' objectives might influence the cost and effectiveness of DSTs' outputs. Improving the ability of DSTs to incorporate objectives consistent with policy and stakeholders' values (e.g., restore certain species or sedimentation control) across management scales can help close the gap between tool recommendations and management decisions while making the barrier removal prioritization process transparent and efficient.

Lin, H. Y., Robinson, K. F., & Walter, L. (2020). Trade-Offs among Road-Stream Crossing Upgrade Prioritizations Based on Connectivity Restoration and Erosion Risk Control. *River Research and Applications,* 36(3), 371-382. https://doi.org/10.1002/rra.3593

Prioritizing projects to improve cost-effectiveness has become a common practice in natural resources management, especially in selecting sites for river restoration work. Previous studies for prioritizing road-stream crossing upgrade projects focused on either restoring river connectivity or reducing sedimentation, even though crossings can affect connectivity and sedimentation simultaneously. In this study, we simulated site selection to maximize the improvement of connectivity restoration and sedimentation reduction of three prioritization schemes targeting (a) river connectivity, (b) erosion risk, or (c) both objectives concurrently and compared the results. Furthermore, we examined the relationships between the cost-effectiveness of prioritizations and watershed characteristics. We found significant differences among the effectiveness of prioritization objectives; thus, trade-offs should be taken into consideration when prioritizing crossings. The incorporation of spatial interdependency among crossings and weighting objectives could significantly change the cost-effectiveness. We also found that splitting the budget and using a portion to individually prioritize each objective could be more cost-effective than using the whole budget to achieve concurrent objectives. Watershed characteristics like size and connectivity- and sedimentation-related factors could be used to help identify effective management for both connectivity restoration and sedimentation control.

McLaughlin, R. L., Smyth, E. R. B., Castro-Santos, T., Jones, M. L., Koops, M. A., Pratt, T. C., & Velez-Espino, L. A. (2013). Unintended Consequences and Trade-Offs of Fish Passage. *Fish and Fisheries,* 14(4), 580-604. https://doi.org/10.1111/faf.12003

We synthesized evidence for unintended consequences and trade-offs associated with the passage of fishes. Provisioning of fish passageways at dams and dam removals are being carried out increasingly as resource managers seek ways to reduce fragmentation of migratory fish populations and restore biodiversity and nature-like ecosystem services in tributaries altered by dams. The benefits of provisioning upstream passage are highlighted widely. Possible unwanted consequences and trade-offs of upstream passage are coming to light, but remain poorly examined and underappreciated. Unintended consequences arise when passage of native and desirable introduced fishes is delayed, undone (fallback), results in patterns of movement and habitat use that reduce Darwinian fitness (e.g. ecological traps), or is highly selective taxonomically and numerically. Trade-offs arise when passage decisions intended to benefit native species interfere with management decisions intended to control the unwanted spread of non-native fishes and aquatic invertebrates, or genes, diseases and contaminants carried by hatchery and wild fishes. These consequences and trade-offs will vary in importance from system to system and can result in large economic and environmental costs. For some river systems, decisions about how to manage fish passage involve substantial risks and could benefit from use of a formal, structured process that allows transparent, objective and, where possible, quantitative evaluation of these risks. Such a process can also facilitate the design of an adaptive framework that provides valuable insights into future decisions.

Milt, A. W., Doran, P. J., Ferris, M. C., Moody, A. T., Neeson, T. M., & McIntyre, P. B. (2017). Local-Scale Benefits of River Connectivity Restoration Planning Beyond Jurisdictional Boundaries. *River Research and Applications,* 33(5), 788-795. https://doi.org/10.1002/rra.3135

Conservation planning aims to optimize outcomes for select species or ecosystems by directing resources toward high-return sites. The possibility that local benefits might be increased by directing resources beyond the focal area is rarely considered. We present a case study of restoring river connectivity for migratory fish of the Great Lakes Basin by removing dams and road crossings within municipal jurisdictions versus their broader watersheds. We found that greater river connectivity could often be achieved by considering both intra-jurisdictional and extra-jurisdictional barriers. Focusing on jurisdictional barriers alone generally forfeited <20% (median = 0%) of habitat gains for those who value solely habitat gains within the jurisdiction, but > 75% (median = 100%) for planners who value larger-scale habitat gains. Similarly, cost savings tended to be between -50% and +50%, but in some cases were very negative. Our study underscores the local-scale benefits of broadening restoration investments, especially for decision makers of the Great Lakes Basin and contributes to a discussion of appropriate and efficient scales of conservation planning.

Moody, A. T., Neeson, T. M., Wangen, S., Dischler, J., Diebel, M. W., Milt, A., . . . McIntyre, P. B. (2017). Pet Project or Best Project? Online Decision Support Tools for Prioritizing Barrier Removals in the Great Lakes and Beyond. *Fisheries,* 42(1), 57-65. https://doi.org/10.1080/03632415.2016.1263195

Structures that block movement of fish through river networks are built to serve a variety of societal needs, including transportation, hydroelectric power, and exclusion of exotic species. Due to their abundance, road crossings and dams reduce the amount of habitat available to fish that migrate from the sea or lakes into rivers to breed. The benefits to fish of removing any particular barrier depends on its location within the river network, its passability to fish, and the relative position of other barriers within the network. Balancing the trade-offs between ecological and societal values makes choosing among potential removal projects difficult. To facilitate prioritization of barrier removals, we developed an online decision support tool (DST) with three functions: (1) view existing barriers at various spatial scales; (2) modify information about barriers, including removal costs; and (3) run optimization models to identify portfolios of removals that provide the greatest amount of habitat access for a given budget. A survey of available DSTs addressing barrier removal prioritization indicates that barrier visualization is becoming widespread but few tools allow dynamic calculation of connectivity metrics, scenario analysis, or optimization. Having these additional functions, our DST enables organizations to develop barrier removal priorities based on cost-effectiveness in restoring aquatic connectivity.

Neeson, T. M., Ferris, M. C., Diebel, M. W., Doran, P. J., O'Hanley, J. R., & McIntyre, P. B. (2015). Enhancing Ecosystem Restoration Efficiency through Spatial and Temporal Coordination. *Proceedings of the National Academy of Sciences of the United States of America,* 112(19), 6236-6241. https://doi.org/10.1073/pnas.1423812112

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.

Neeson, T. M., Moody, A. T., O'Hanley, J. R., Diebel, M., Doran, P. J., Ferris, M. C., . . . McIntyre, P. B. (2018). Aging Infrastructure Creates Opportunities for Cost-Efficient Restoration of Aquatic Ecosystem Connectivity. *Ecological Applications,* 28(6), 1494-1502. https://doi.org/10.1002/eap.1750

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

O'Hanley, J. R., Wright, J., Diebel, M., Fedora, M. A., & Soucy, C. L. (2013). Restoring Stream Habitat Connectivity: A Proposed Method for Prioritizing the Removal of Resident Fish Passage Barriers. *Journal of Environmental Management,* 125, 19-27. https://doi.org/10.1016/j.jenvman.2013.02.055

Systematic methods for prioritizing the repair and removal of fish passage barriers, while growing of late, have hitherto focused almost exclusively on meeting the needs of migratory fish species (e.g., anadromous salmonids). An important but as of yet unaddressed issue is the development of new modeling approaches which are applicable to resident fish species habitat restoration programs. In this paper, we develop a budget constrained optimization model for deciding which barriers to repair or remove in order to maximize habitat availability for stream resident fish. Habitat availability at the local stream reach is determined based on the recently proposed C metric, which accounts for the amount, quality, distance and level of connectivity to different stream habitat types. We assess the computational performance of our model using geospatial barrier and stream data collected from the Pine-Popple Watershed, located in northeast Wisconsin (USA). The optimization model is found to be an efficient and practical decision support tool. Optimal solutions, which are useful in informing basin-wide restoration planning efforts, can be generated on average in only a few minutes.

Zheng, P. Q., & Hobbs, B. F. (2013). Multiobjective Portfolio Analysis of Dam Removals Addressing Dam Safety, Fish Populations, and Cost. *Journal of Water Resources Planning and Management,* 139(1), 65-75. https://doi.org/10.1061/(asce)wr.1943-5452.0000209

Decisions concerning dam removal or retention are challenging because they involve tradeoffs, diverse stakeholders, and increasing public safety concerns. A multiobjective portfolio optimization approach, implemented as an integer linear program (ILP), identifies efficient portfolios of dam removals in terms of the objectives of public safety, fish population health, and cost. The ILP integrates judgments by dam

safety experts with the results of ecosystem simulations and statistical analysis of empirical data, to explore tradeoffs among the three objectives when choosing a portfolio of dams to be removed in multiple watersheds. This methodology is applied to a case study including 139 dams in 10 watersheds of the Lake Erie basin. Significant tradeoffs are found between maximizing fish population health and minimizing safety risks under a given budget, with different dams recommended for removal in each case. Also, the way dam safety risk is quantified in the ILP affects the selected set, and therefore, deserves further research. Overall, the multiobjective portfolio analysis approach provides a simple, flexible, and useful tool for policy makers to explore the nature and magnitude of tradeoffs to screen potential dam removal projects.

South America

Laborde, A., Habit, E., Link, O., & Kemp, P. (2020). Strategic Methodology to Set Priorities for Sustainable Hydropower Development in a Biodiversity Hotspot. *Science of the Total Environment,* 714, 9. https://doi.org/10.1016/j.scitotenv.2020.136735

Massive exploitation of freshwater systems for hydropower generation in developing countries is challenging sustainability due to cumulative environmental impacts in regions with high endemism. Habitat fragmentation is recognized as a major impact on river ecosystems. The nature and magnitude of connectivity loss depend on characteristics of the hydropower projects, and of the threatened fish communities. In areas where appropriate mitigation technology is lacking, there is a need to identify the fish species that arc most at risk to better concentrate efforts. This paper aimed to set conservation priorities for sustainable hydropower development by analyzing native fish species and project characteristics. The Chilean ichthyogeographic province, an ecoregion with high endemism and massive hydropower projects development, has been considered as a case study. By using overlapping information on the characteristics of 1124 hydropower projects and distribution of native fish species, we identified three project categories of projects based on their need for mitigation. These were projects where mitigation was considered: a) not required (15%), b) required and feasible (35%), and c) required but challenging (50%). Projects where mitigation was not required were located at sites where native fish were absent and/or where water intakes allowed fish to pass. Interestingly, projects where mitigation was feasible were inhabited by a species assemblage that comprised the genus Trichomycterus, Diplomystes and Percilia, and the species Ch. pisciculus and B. maldona doi . This finding emphasizes the need to develop a multispecific fishway that can accommodate this group. Projects where mitigation would be difficult to achieve were located at sites with a variety of different assemblages, thus making a standard fish pass solution challenging and site-specific. This study advances understanding for the need to develop mitigation strategies and technologies in ecoregions of high endemism threatened by hydropower and to prioritize the construction of planned projects.

O'Hanley, J. R., Pompeu, P. S., Louzada, M., Zambaldi, L. P., & Kemp, P. S. (2020). Optimizing Hydropower Dam Location and Removal in the Sao Francisco River Basin, Brazil to Balance Hydropower and River Biodiversity Tradeoffs. *Landscape and Urban Planning,* 195, 9. https://doi.org/10.1016/j.landurbplan.2019.103725

To support eco-friendly hydropower planning in developing regions, we propose a spatial optimization model for locating dams to balance tradeoffs between hydropower generation and migratory fish species richness. Our model incorporates two special features. First, it is tailored to the dispersal of tropical migratory fishes, which typically require long, unimpeded river stretches to complete their life-cycle. To model fish with this type of dispersal pattern, we introduce the concept of a river pathway, which represents a novel way to describe river connectivity. Second, it combines decisions about dam placement and removal, thus facilitating opportunities for hydropower offsetting. We apply our model to the Sao Francisco River basin, Brazil, an area of hydropower-freshwater biodiversity conflict. We find that dams have reduced weighted migratory fish richness 51% compared to a pre-dam baseline. We also find that even limited dam removal has the potential to significantly enhance fish biodiversity. Offsetting the removal of a single dam by the optimal siting of new dams could increase fish richness by 25% above the current average. Moving forward, optimizing new dam sites to increase hydropower by 20%, rather than selecting the fewest number of dams, could reduce fish species losses by 89%. If decisions about locating new dams are combined with dam removal, then a win-win can even be achieved with 20% greater hydropower and 19% higher species richness. Regardless of hydropower targets and dam removal options, a key observation is that optimal sites for dams are mostly located in the upper reaches of the basin rather than along the main stem of the Sao Francisco River or its main tributaries.

Europe

Atkinson, S., Bruen, M., O' Sullivan, J. J., Turner, J. N., Ball, B., Carlsson, J., . . . Kelly-Quinn, M. (2020). An Inspection-Based Assessment of Obstacles to Salmon, Trout, Eel and Lamprey Migration and River Channel Connectivity in Ireland. *Science of the Total Environment,* 719, 13. https://doi.org/10.1016/j.scitotenv.2020.137215

Knowledge of the location, physical attributes and impacts of obstades on river connectivity is a requirement for any mitigating action aimed at restoring the connectivity of a river system. Here, we present a study that recorded the numbers and physical diversity of obstades in 10 river catchments in Ireland, together with the impact these structures had on overall river connectivity. A total of 372 obstacles were recorded, 3 of these were dams, and the remainder were low-head weirs/sluices, obstacles associated with mad or rail crossings of rivers and natural structures. The degree of fragmentation was estimated in each catchment by calculating obstacle density and the Dendrific Connectivity Index (DCI). DCI scores were calculated for 4 native Irish fish species with different life-histories, namely diadromous (Atlantic salmon, sea trout, European eel, sea lamprey) and potamodromous (brown trout). Obstacle density ranged between 12 and 0.02 obstades/km of river. Six of the 10 catchments had at least one obstacle located on the mainstem river at least 5 km from its mouth/confluence. These 6 catchments typically had the lowest connectivity scores for diadromous species and ranged between 0.6 and 44.1 (a fully connected river would receive a maximum score of 100). While there was no significant correlation between obstacle density and the DCI score for diadromous fish, a significant negative correlation was detected between obstacle density and the DCI score for potamodromous brown trout Here, we highlight the merit of these obstacle assessments and associated challenges for decision-making relating to prioritisation of obstacles for removal or modification.

Atkinson, S., Bruen, M., Turner, J. N., Ball, B., Bullock, C., O'Sullivan, J. J., . . . Kelly-Quinn, M. (2018). The Value of a Desk Study for Building a National River Obstacle Inventory. *River Research and Applications,* 34(8), 1085-1094. https://doi.org/10.1002/rra.3338

This study evaluates two desk-based approaches for building an inventory of man-made river obstacles. The creation of a river obstacle inventory is a vital first step in developing a prioritization process for obstacle removal and/or modification. In this study, a desktop geographical information system analysis of two rivers and their tributary network was undertaken, using two different approaches. The first involved analysing historical maps, satellite imagery, and Ordnance Survey Ireland Discovery Series maps and producing a geo-referenced layer of all the potential river obstacles. The second involved developing a geo-referenced layer of potential river obstacles based on the intersections between elements of the transport network (roads and railways) and river systems. To determine the effectiveness of the desk studies, the located obstacles were cross-referenced with actual obstacles verified through a field survey. The desk studies identified several thousand potential obstacles. The study utilizing a range of maps consistently located a greater number of actual obstacles than the desk study based on intersections between the transport and river networks. The results indicate that desk-based research offers an efficient and effective method for locating river obstacles and can guide subsequent field surveys aimed at confirming the presence of obstacles. This is particularly useful for eliminating from study large stretches of rivers that would otherwise need to be walked to confirm the presence, or otherwise, of potential river obstacles. In this regard, desk-based exercises can offer opportunities to save on both time and cost in larger river assessments.

Barry, J., Coghlan, B., Cullagh, A., Kerr, J. R., & King, J. J. (2018). Comparison of Coarse-Resolution Rapid Methods for Assessing Fish Passage at Riverine Barriers: Ice and Sniffer Protocols. *River Research and Applications,* 34(9), 1168-1178. https://doi.org/10.1002/rra.3358

Man-made barriers have led to river fragmentation, restricting fish migrations to critical habitat. Fragmentation is relevant to the Water Framework and Habitats (Annex II fish) Directives of the European Union. SNIFFER (Water Framework Directive 111) is a United Kingdom-developed fish passability assessment method with passability scores based on published data describing the physiological abilities of different fish species/life stages. SNIFFER is an objective protocol, but final scores require assessor opinion on specific nonquantified elements. The French ICE fish passability assessment protocol covers a larger number of fish species/life stages and removes the requirement for velocity readings (except in a few situations) and expert opinion with assessors following a decision tree process. In most situations, fewer direct measurements are required for the ICE protocol, and the evaluation process is quicker and simpler. Both protocols utilize a similar passability scoring system (0 = total barrier, 0.3 = high impact, 0.6 = low impact, 1 = no risk). Comparison of outcomes for species categories for both protocols was made in paired comparisons for 112 transversal sections (fish passage routes) recorded at 52 barriers (in-river structures) of varying complexity in Irish rivers. Overall scores were found to be in high agreement for species groups at impassable (Score 0) and no risk (Score 1) barriers. Protocol agreement dropped significantly for high-impact (Score 0.3) and low-impact (Score 0.6) barriers. Results are discussed in the context of barrier passability at the 52 structures examined, primarily in the context of Atlantic salmon (Salmo salar L.) and of sea lamprey (Petromyzon marinus L.). In total, 22 of the structures had one or more fishways or fish passage solutions built into them as part of the original design. Both protocols identified substantial problems for sea lamprey and adult salmon

at the majority of the fish passage solutions surveyed. The merits and shortcomings of both protocols, for managers assessing fish passability at complex riverine structures, are discussed.

Branco, P., Segurado, P., Santos, J. M., & Ferreira, M. T. (2014). Prioritizing Barrier Removal to Improve Functional Connectivity of Rivers. *Journal of Applied Ecology,* 51(5), 1197-1206. https://doi.org/10.1111/1365-2664.12317

1. Freshwater systems are severely impacted by connectivity reduction due to the construction of dams and weirs. The breach of this longitudinal connectivity imperils freshwater fish species world-wide. There is thus an increasing need for numerical tools that help decision-makers correctly allocate resources to prioritize restoration actions. 2. This study provides a methodology for prioritizing the removal of barriers. It is based on spatial graphs, which represent structural units as nodes and relationships between nodes as links, and uses habitat suitability modelling (Boosted Regression Trees) to weight nodes. To exemplify the application of this procedure, we used the Tagus River network and evaluated the impact of the dams (29 built between 1928 and 2004) on the occurrence of each of two fish species (Iberian barbel Luciobarbus bocagei - representing large potamodromous fish; and southern Iberian chub Squalius pyrenaicus - representing small water-column residents) and on the combination of both. 3. Results show that dam construction on the Tagus was responsible for a 48.4-54.4% reduction in river connectivity for different fish species. Actions to promote connectivity in just seven of the dams would increase connectivity by 35.0-37.2%. 4. The removal of a single barrier chosen through prioritization had a greater overall connectivity increase than the random removal of seven barriers. 5. Synthesis and applications. The proposed prioritization method, using spatial graphs and habitat suitability modelling, makes it possible to model the impact of the removal or placement of an insurmountable barrier on the overall functional connectivity of a river network, facilitating resource allocation and minimizing the impact of new barrier implementation.

Breve, N. W. P., Buijse, A. D., Kroes, M. J., Wanningen, H., & Vriese, F. T. (2014). Supporting Decision-Making for Improving Longitudinal Connectivity for Diadromous and Potamodromous Fishes in Complex Catchments. *Science of the Total Environment,* 496, 206-218. https://doi.org/10.1016/j.scitotenv.2014.07.043

Preservation and restoration of Europe's endangered migratory fish species and habitats are high on the international river basin policy agenda. Improvement through restoration of longitudinal connectivity is seen as an important measure, but although prioritization of in-stream barriers has been addressed at local and regional levels the process still lacks adequate priority on the international level. This paper introduces a well-tested method, designed to help decision makers achieve the rehabilitation of targeted ichthyofauna more successfully. This method assesses artificial barriers within waters designated under the Water Framework Directive (WFD), Europe's main legislative driver for ecological improvement of river basins. The method aggregates migratory fish communities (both diadromous and potamodromous) into functional biological units (ecological fish guilds) and defines their most pressing habitat requirements. Using GIS mapping and spatial analysis of the potential ranges (fish zonation) we pin-point the most important barriers, per guild. This method was developed and deployed over a 12 year period as a practical case study, fitting data derived from the 36 regional water management organisations in the Netherlands. We delivered national advice on the prioritization of a total of 2924

barriers located within WFD water bodies, facilitating migration for all 18 indigenous migratory fish species. Scaling up to larger geographical areas can be achieved using datasets from other countries to link water body typologies to distribution ranges of migratory fish species.

Buddendorf, W. B., Jackson, F. L., Malcolm, I. A., Millidine, K. J., Geris, J., Wilkinson, M. E., & Soulsby, C. (2019). Integration of Juvenile Habitat Quality and River Connectivity Models to Understand and Prioritise the Management of Barriers for Atlantic Salmon Populations across Spatial Scales. *Science of the Total Environment,* 655, 557-566. https://doi.org/10.1016/j.scitotenv.2018.11.263

Diadromous fish populations are strongly affected by in-stream barriers that cause river network fragmentation, constraining productivity or preventing completion of their lifecycle. Removal or reduction of barrier impacts is a restoration measure associated with unambiguous benefits. Management of barriers is therefore often prioritised above other restoration actions. Barrier management is prioritised at local and national scales depending on funding. However, barrier prioritisation is potentially sub-optimal because existing tools do not consider habitat quality. Furthermore, effects of partial barriers (those passable under certain conditions) are uncertain, depending on location and potential cumulative effects. A framework is presented for assessing effects of impassable manmade barriers (IMBs) on longitudinal river network connectivity (percentage of upstream habitat accessible from the river mouth) for Atlantic salmon across spatial scales, using Scotland as an example. The framework integrates juvenile habitat quality and network connectivity models to (1) provide information necessary for local and national prioritisation of barriers, and (2) assess potential effects of passable manmade barriers (PMBs) within a sensitivity framework. If only IMBs are considered, high levels of longitudinal connectivity are observed across most of Scotland's rivers. Barrier prioritisation is sensitive to habitat weighting: not accounting for habitat quality can lead to over-or underestimating the importance of IMBs. Prioritisation is also highly sensitive to the passability of PMBs: if passability drops to <97% (combined up-and downstream passability), the mean effect of PMBs becomes greater than IMBs at the national level. Moreover, impacts on catchment connectivity, and thus production (number of juvenile salmon produced by the river), could be severe, suggesting a better understanding of the passability of PMBs is important for future management of migration barriers. The presented framework can be transferred to other catchments, regions, or countries where necessary data are available, making it a valuable tool to the broader restoration community.

Cortes, R. M. V., Peredo, A., Terencio, D. P. S., Fernandes, L. F. S., Moura, J. P., Jesus, J. J. B., . . . Pacheco, F. A. L. (2019). Undamming the Douro River Catchment: A Stepwise Approach for Prioritizing Dam Removal. *Water,* 11(4), 17. https://doi.org/10.3390/w11040693

Dams provide water supply, flood protection, and hydropower generation benefits, but also harm native species by altering the natural flow regime, and degrading the aquatic and riparian habitats. In the present study, which comprised the Douro River basin located in the North of Portugal, the cost-benefit assessment of dams was based upon a balance between the touristic benefits of a dammed Douro, and the ecological benefits of less fragmented Douro sub-catchments. Focused on four sub-catchments (Sabor, Tamega, Coa and Corgo), a probabilistic stream connectivity model was developed and implemented to recommend priorities for dam removal, where this action could significantly improve

the movement of potadromous fish species along the local streams. The proposed model accounts for fish movement across the dam or weir (permeability), which is a novel issue in connectivity models. However, before any final recommendation on the fate of a dam or weir, the connectivity results will be balanced with other important socio-economic interests. While implementing the connectivity model, an inventory of barriers (dams and weirs) was accomplished through an observation of satellite images. Besides identification and location of any obstacles, the inventory comprised the compilation of data on surrounding land use, reservoir water use, characteristics of the riparian gallery, and permeability conditions for fish, among others. All this information was stored in a geospatial dataset that also included geographical information on the sub-catchment drainage network. The linear (drainage network) and point (barriers) source data were processed in a computer program that provided or returned numbers for inter-barrier stream lengths (habitat), and the barrier permeability. These numbers were finally used in the same computer program to calculate a habitat connector index, and a link improvement index, used to prioritize dam removal based upon structural connectivity criteria. The results showed that habitat patch connectivity in the Sabor, Tamega and Coa sub-catchments is not dramatically affected by the installed obstacles, because most link improvement values were generally low. For the opposite reason, in the Corgo sub-catchment, obstacles may constitute a relatively higher limitation to connectivity, and in this case the removal of eight obstacles could significantly improve this connectivity. Using the probabilistic model of structural connectivity, it was possible to elaborate a preliminary selection of dams/weirs that critically limit stream connectivity, and that will be the focus of field hydraulic characterization to precisely determine fish movement along the associated river stretches. Future work will also include the implementation of a multi-criteria decision support system for dam removal or mitigation of the critical structures, as well to define exclusion areas for additional obstacles.

King, S., O'Hanley, J. R., Newbold, L. R., Kemp, P. S., & Diebel, M. W. (2017). A Toolkit for Optimizing Fish Passage Barrier Mitigation Actions. *Journal of Applied Ecology,* 54(2), 599-611. https://doi.org/10.1111/1365-2664.12706

1. The presence of dams, stream-road crossings and other infrastructure often compromises the connectivity of rivers, leading to reduced fish abundance and diversity. The assessment and mitigation of river barriers is critical to the success of restoration efforts aimed at restoring river integrity. 2. In this study, we present a combined modelling approach involving statistical regression methods and mixed integer linear programming to maximize resident fish species richness within a catchment through targeted barrier mitigation. Compared to existing approaches, our proposed method provides enhanced biological realism while avoiding the use of complex and computationally intensive population/ecosystem models. 3. To estimate barrier passability quickly and at low cost, we further outline a rapid barrier assessment methodology. The methodology is used to characterize potential passage barriers for various fish species common to the UK but can be readily adapted to different planning areas and other species of interest. 4. We demonstrate the applicability of our barrier assessment and prioritization approach based on a case study of the River Wey, located in south-east England. We find that significant increases in species richness can be achieved for modest investment in barrier mitigation. In particular, dams and weirs with low passability located on mid-to high-order streams are identified as top priorities for mitigation. 5. Synthesis and applications. Our study shows the benefits of combining a coarse resolution barrier assessment methodology with state-of-the-art optimization modelling to cost-effectively plan fish passage barrier mitigation actions. The modelling approach can help inform on-the-ground river restoration decision-making by providing a recommended

course of action that best allocates limited resources in order to restore longitudinal connectivity and maximize ecological gains.

Langhans, S. D., Gessner, J., Hermoso, V., & Wolter, C. (2016). Coupling Systematic Planning and Expert Judgement Enhances the Efficiency of River Restoration. *Science of the Total Environment,* 560, 266-273. https://doi.org/10.1016/j.scitotenv.2016.03.232

Ineffectiveness of current river restoration practices hinders the achievement of ecological quality targets set by country-specific regulations. Recent advances in river restoration help planning efforts more systematically to reach ecological targets at the least costs. However, such approaches are often desktop-based and overlook real-world constraints. We argue that combining two techniques commonly used in the conservation arena - expert judgement and systematic planning - will deliver cost-effective restoration plans with a high potential for implementation. We tested this idea targeting the restoration of spawning habitat, i.e. gravel bars, for 11 rheophilic fish species along a river system in Germany (Havel-Spree rivers). With a group of local fish experts, we identified the location and extent of potential gravel bars along the rivers and necessary improvements to migration barriers to ensure fish passage. Restoration cost of each gravel bar included the cost of the action itself plus a fraction of the cost necessary to ensure longitudinal connectivity by upgrading or building fish passages located downstream. We set restoration targets according to the EU Water Framework Directive, i.e. relative abundance of 11 fish species in the reference community and optimised a restoration plan by prioritising a subset of restoration sites from the full set of identified sites, using the conservation planning software Marxan. Out of the 66 potential gravel bars, 36 sites which were mainly located in the downstream section of the system were selected, reflecting their cost-effectiveness given that fewer barriers needed intervention. Due to the limited overall number of sites that experts identified as being suitable for restoring spawning habitat, reaching abundance-targets was challenged. We conclude that coupling systematic river restoration planning with expert judgement produces optimised restoration plans that account for on-the-ground implementation constraints. If applied, this approach has a high potential to enhance overall efficiency of future restoration efforts.

Mader, H., & Maier, C. (2008). A Method for Prioritizing the Reestablishment of River Continuity in Austrian Rivers. *Hydrobiologia,* 609, 277-288. https://doi.org/10.1007/s10750-008-9406-0

River continuity is one of the hydro-morphological elements supporting the classification of the ecological status of rivers. In order to achieve good ecological status in the continuity of rivers, the impacts of anthropogenic activities must be limited to the extent that some fish age classes may be missing and there may only be slight changes in species composition and abundance from the type specific community. The main goal of the project is to list priorities for removing obstruction to migration within 12 years to reestablish river continuity so as to allow undisturbed migration of aquatic organisms. The ecological status of the river, the cost-benefit ratio of the proposed restoration and the distance between obstructions are analysed. More than 200 obstructions in about 170 km of river were evaluated. A 1st ranking of the parameter "extension of undisturbed river length" shows significant alterations in comparison with the 2nd and 3rd ranking, where the river length is weighted over the parameters "ecological status" of the river reach and the "cost-benefit ratio" of the measure. The ecological status is classified by comparing the present versus the potential natural morphological

conditions (Leitbild). The cost-benefit ratio takes into account the increase of the fish species composition and the cost of the measures in relation to local circumstances of available property and height of the drop. Examples of obstructions in the Pinka R. move back in the priority list to a maximum of -9 places and forwards to a maximum of +8 places. As a result the list of obstructions by priority for removal to be removed first at the top is analysed. The financial policy and a schedule for removal for the period 2003-2015 are based upon the results of the priority list.

Nunn, A. D., & Cowx, I. G. (2012). Restoring River Connectivity: Prioritizing Passage Improvements for Diadromous Fishes and Lampreys. *Ambio,* 41(4), 402-409. https://doi.org/10.1007/s13280-012-0281-6

Physical obstructions are becoming increasingly recognized as major factors influencing the migrations, population structures, spawning success and recruitment of freshwater organisms. This paper presents a simple but effective method, intended for use by environmental managers, government agencies and conservation bodies, of rapidly assessing and prioritizing barriers to the migrations of diadromous fishes and lampreys for passage improvements. A prioritization matrix was developed using information on fish stock status, the passage efficiency of fishes at individual structures, the distance from the tidal limit and the passability of downstream barriers, and the quantity and quality of habitat upstream of each structure. Importantly, the 'Likelihood of access' was incorporated into the matrix to account for passage efficiency at downstream barriers. Barriers ranked as the highest priority for passage improvements were those characterized by poor fish stocks upstream, low passage efficiency, easy passage from downstream, and a large quantity and high quality of habitat upstream. Prioritization of migration barriers should ensure that access improvements are targeted to achieve optimum benefits.

Rodeles, A. A., Galicia, D., & Miranda, R. (2020). A New Method to Include Fish Biodiversity in River Connectivity Indices with Applications in Dam Impact Assessments. *Ecological Indicators,* 117, 9. https://doi.org/10.1016/j.ecolind.2020.106605

Different indices have been developed to quantify the extent and severity of river fragmentation. These indices vary depending on the specific goals of the study. Here, we present a new Conservation Connectivity Index (CCIP) for potamodromous fish species that considers the conservation value (richness, rarity and vulnerability) of river segments. The Iberian Peninsula holds > 20 endemic and endangered potamodromous fish species as well as > 1000 large dams (> 1 hm(3) of capacity). The CCIP was calculated for the eight most important river basins of the Iberian Peninsula and compared to the Dendritic Connectivity Index (DCIP) developed by Cote et al. in 2009, which uses only river length as a habitat variable. With the use of both DCIP and CCIP, the dams were analysed and ranked according to their impacts on the river basin. The main results show that Iberian river basins are heavily fragmented, with river basin connectivity percentages of less than 20% in most cases using both DCIP and CCIP. CCIP values are slightly higher than DCIP values in almost all cases. When the impact of individual dams is analysed, differences also appear between the DCIP and CCIP. CCIP highlights the impact of dams located in areas of high fish conservation value while DCIP emphasize the impact of dams fragmenting large river segments. The CCIP appears to be adequate to highlight important sites for conservation in river connectivity studies. It could be applied in different studies and river basins around the world to prioritize dam removals or plan new dam locations.

Roy, M. L., & Le Pichon, C. (2017). Modelling Functional Fish Habitat Connectivity in Rivers: A Case Study for Prioritizing Restoration Actions Targeting Brown Trout. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 27(5), 927-937. https://doi.org/10.1002/aqc.2786

1. Throughout the world, decreased connectivity of fluvial habitats caused by artificial river channel alterations such as culverts, weirs and dykes is seen as an important threat to the long-term survival of many aquatic species. In addition to assessing habitat quality and abundance, wildlife managers are becoming increasingly aware of the importance of taking into account habitat connectivity when setting priorities for restoration. In this paper, a new approach of spatial analysis adapted to rivers and streams is proposed for modelling 2D functional habitat connectivity, integrating distance, costs and risk of travelling between habitat patches (e.g. daily use, spawning, refuge) for particular fish species, size classes and life stages. 2. This approach was applied to a case study in which brown trout (Salmo trutta) habitat accessibility was examined and compared under various scenarios of stream restoration in a highly fragmented stream in Ile-de-France. Probabilities of reaching spawning habitats were estimated from a trout-populated area located downstream of the barriers and from potential daily-use habitat patches across the stream segment. 3. The approach successfully helped prioritize restoration actions by identifying options that yield the greatest increase in accessible spawning habitat areas and connectivity between spawning habitat and daily-use habitat patches. This case study illustrates the practical use of the approach and the software in the context of river habitat management.

Segurado, P., Branco, P., Avelar, A. P., & Ferreira, M. T. (2015). Historical Changes in the Functional Connectivity of Rivers Based on Spatial Network Analysis and the Past Occurrences of Diadromous Species in Portugal. *Aquatic Sciences,* 77(3), 427-440. https://doi.org/10.1007/s00027-014-0371-6

The disruption of longitudinal connectivity caused by artificial barriers in rivers is considered to be a major threat to freshwater fish communities at the global scale. In Portugal, the construction of several big dams all through the 20th century was a major cause of disappearance or decline of long distance migratory fish species from various rivers. In this study we analysed the historical changes of functional connectivity for diadromous fish at the Tagus basin river network (Portugal), using a spatial graph approach that integrates both structural connectivity and habitat suitability. Due to the presence of many artificial barriers, the current distribution of species does not reflect natural environmental conditions. Therefore, historical data on the occurrence of species is paramount to assess the potential habitat suitability. The compilation of historical data on the distribution of diadromous species [Sea Lamprey-Petromyzon marinus (Linnaeus 1758) and Allis shad-Alosa alosa (Linnaeus 1758)] was based on geographical dictionaries and geo-referenced information for Portugal dated between 1700 and 1900. Habitat suitability was expressed as the probabilities of occurrence of empirical predictive models based on the historical records and a set of regionalized environmental data. The loss of connectivity caused by big dam construction between 1928 and 2004 was then analysed using a spatial graph approach. The output of this analysis will aid decision-makers to optimize targets of connectivity restoration actions aiming at enhancing the functional connectivity of the river network for diadromous species, using the historical situation as a benchmark.

Segurado, P., Branco, P., & Ferreira, M. T. (2013). Prioritizing Restoration of Structural Connectivity in Rivers: A Graph Based Approach. *Landscape Ecology,* 28(7), 1231-1238. https://doi.org/10.1007/s10980-013-9883-z

Longitudinal connectivity is considered a key issue in river management, as it shapes ecological processes from single organisms to populations and ecosystems. Recently, it was shown that network analysis based on spatial graphs has promising applications as a tool for the assessment of connectivity in riverine systems. In this study we used a graph theory approach to identify which barriers most impacted the structural connectivity of a river basin and which connections should preferably be restored or enhanced in order to effectively improve the overall connectivity. An innovative aspect of the proposed methodology is the consideration of the cumulative non-additive impacts produced by barriers, which are especially relevant to organisms of high mobility such as fish. The portuguese river Tagus basin was used as a case study. The cumulative effect of barriers was studied using two approaches: (1) an historical approach in which the impact of barriers was assessed sequentially following the historical succession of construction; (2) a "backward" approach in which barriers were sequentially removed according to their impact. The overall structural connectivity of the river basin decreased to about 50 % of its original value after the major dams were constructed. Results show that it would be necessary to rehabilitate 11 connections in order to increase the overall structural connectivity to 90 % of its original value. This work proposes a novel and straightforward approach to prioritize rehabilitation actions in river systems, providing a promising tool for decision-makers.

Valbuena-Castro, J., Fuentes-Perez, J. F., Garcia-Vega, A., Bravo-Cordoba, F. J., Ruiz-Legazpi, J., Paredes, A. M. D., & Sanz-Ronda, F. J. (2020). Coarse Fishway Assessment to Prioritize Retrofitting Efforts: A Case Study in the Duero River Basin. *Ecological Engineering,* 155, 10. https://doi.org/10.1016/j.ecoleng.2020.105946

Restoring the longitudinal connectivity of rivers is one of the main objectives of environmental European directives and policies. Fish passes or fishways are one of the most common actions for its restoration. Despite the great number of fish passes constructed during the last two decades to comply with these policies, few of them have been assessed and their suitability for fish movements is unknown. There are different options to assess fish passes, but time and economic costs frequently limit their application. Coarse fishway assessment methods (CFAMs) are an easy, fast and economic alternative for this purpose. This study aims to display the potential of CFAMs to evaluate a large number of fishways, to show the actual status of fishways in an Iberian representative river basin, and to diagnose their suitability and problems. For this, the Spanish Duero River Authority promoted the assessment of 64 stepped fishways in the Duero River basin (Spain) using the AEPS methodology. The results were analyzed considering the four stages that a fish must overcome in a fishway (attraction, entry, passage and exit), the fishway type and the construction period. Among others, results show that 50% of the assessed fishways allow the free movement of fish. However, this percentage could have been greater applying an adequate monitoring program for the fishway design and construction. Furthermore, the diagnosis by stages of the AEPS methodology allowed to identify the attraction and passage as the most problematic stages and also helped to define specific retrofitting solutions for each fishway. The study concludes that the application of CFAM during fishway design, construction and first operation stages can increase their effectiveness and, thus, the number of fish passes that contribute to the restoration of the longitudinal connectivity of rivers.

van Puijenbroek, P., Buijse, A. D., Kraak, M. H. S., & Verdonschot, P. F. M. (2019). Species and River Specific Effects of River Fragmentation on European Anadromous Fish Species. *River Research and Applications,* 35(1), 68-77. https://doi.org/10.1002/rra.3386

Fragmentation is one of the major threats to riverine ecosystems and this is most explicitly expressed by the decline in numbers of migratory fish species. Yet each species has different migration requirements and their natural distribution can include several catchments with multiple dams. Hence, to prioritize candidate rivers for improving accessibility, differences between species and between catchments have to be taken into account. The aim of this study was therefore to analyse the species and river specific effects of river fragmentation on migratory fish on a European scale. The effect of river damming on migratory fish was quantified for all 16 European long- and mid-distance anadromous species and for 33 large European rivers. The historical distribution was compared with the current upstream accessibility of the main river and the current distribution and population status of each species. The observed effects of reduced connectivity were further quantified using the Dendritic Connectivity Index for species and the Fragmentation Index for rivers. Our results showed that only very few rivers are still unaffected by dams in the main stem and that the few remaining viable migratory fish populations in Europe occur in these accessible rivers. Barriers were prioritized for making passable based on the potential accessibility gain and the number of benefitting species, showing that the main stems of the rivers Shannon and Nemunas are the best candidates. It was concluded that evaluating species and river specific effects of fragmentation strongly aids in prioritizing rivers for improving upstream accessibility.

No geographic focus

Kemp, P. S., & O'Hanley, J. R. (2010). Procedures for Evaluating and Prioritising the Removal of Fish Passage Barriers: A Synthesis. *Fisheries Management and Ecology,* 17(4), 297-322. https://doi.org/10.1111/j.1365-2400.2010.00751.x

Techniques for assessing the impact of structural barriers on fish passage and for prioritising restoration actions are reviewed. Current survey methodologies are biased towards specific structures, primarily culverts and economically significant fish. Assessment criteria are often based on swimming capabilities of upstream migrating adult salmonids, while ignoring other life-stages, non-salmonid species, downstream migration and behaviour. The development of comprehensive and centrally owned geospatial inventories of barriers is essential. The collection, maintenance and dissemination of pertinent structural and environmental data can be technically, logistically and financially challenging. Standardised procedures are needed to rapidly and cost-effectively survey large numbers of barriers over wide geographic areas. The prioritisation of barrier repair and removal projects is most often based on simple cost-benefit analysis, whereby individual barriers are scored based on a set of assessment criteria and then ranked in order of priority. The benefits of using scoring-and-ranking systems, however, are unacceptably low because they consider barriers independently, thereby ignoring the cumulative, non-additive impacts produced by multiple, spatially interconnected structures. Optimisation modelling offers a more robust approach for efficiently prioritising decision making in river restoration planning, allowing decision makers to account for key uncertainties and effectively balance multiple, possibly competing, environmental and socioeconomic goals and constraints.

Linke, S., Hermoso, V., & Januchowski-Hartley, S. (2019). Toward Process-Based Conservation Prioritizations for Freshwater Ecosystems. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 29(7), 1149-1160. https://doi.org/10.1002/aqc.3162

Over the last two decades, systematic conservation planning has been increasingly applied in terrestrial and marine systems. The approach has traditionally been lagging in freshwater environments, partly because considering unique ecological processes, such as connectivity and propagation of threats along river networks, is a key factor for conservation success in freshwater landscapes. This review highlights advances in freshwater planning in the last decade, but also discusses areas in need of increased efforts. Including riverine connectivity and disturbances are largely resolved topics. Both processes have been included in major conservation planning software packages and applied globally. Theoretical advances to connectivity in wetlands and groundwater systems have started to appear, but no encompassing framework has emerged. Spatial solutions to conservation planning in lakes do not yet exist. Some headway has been made when dealing with functional connectivity and genetic processes. For the latter, approaches have been developed to deal with cryptic biodiversity and to investigate the adequacy of conservation plans to include genetic diversity. Functional connectivity has been included in conservation plans in ephemeral waterscapes, and initial steps have been made to include migratory species in conservation prioritizations. Conservation planning in socio-ecological landscapes is catching up with biophysical prioritizations. Multiple protection tiers have been realized in river conservation planning frameworks, and freshwater scientists are leading the charge in both multi-objective planning and in including direct functional responses. We conclude that tight integration between ecological sciences and optimization approaches is needed to further process-based conservation planning.

McKay, S. K., Cooper, A. R., Diebel, M. W., Elkins, D., Oldford, G., Roghair, C., & Wieferich, D. (2017). Informing Watershed Connectivity Barrier Prioritization Decisions: A Synthesis. *River Research and Applications,* 33(6), 847-862. https://doi.org/10.1002/rra.3021

Water resources and transportation infrastructure such as dams and culverts provide countless socio-economic benefits; however, this infrastructure can also disconnect the movement of organisms, sediment, and water through river ecosystems. Trade-offs associated with these competing costs and benefits occur globally, with applications in barrier addition (e.g. dam and road construction), reengineering (e.g. culvert repair), and removal (e.g. dam removal and aging infrastructure). Barrier prioritization provides a unique opportunity to: (i) restore and reconnect potentially large habitat patches quickly and effectively and (ii) avoid impacts prior to occurrence in line with the mitigation hierarchy (i.e. avoid then minimize then mitigate). This paper synthesizes 46 watershed-scale barrier planning studies and presents a procedure to guide barrier prioritization associated with connectivity for aquatic organisms. We focus on practical issues informing prioritization studies such as available data sets, methods, techniques, and tools. We conclude with a discussion of emerging trends and issues in barrier prioritization and key opportunities for enhancing the body of knowledge.

McKay, S. K., Martin, E. H., McIntyre, P. B., Milt, A. W., Moody, A. T., & Neeson, T. M. (2020). A Comparison of Approaches for Prioritizing Removal and Repair of Barriers to Stream Connectivity. *River Research and Applications,* n/a(n/a). https://doi.org/10.1002/rra.3684

Dams, road crossings, and water withdrawals extensively fragment rivers, and watersheds often contain hundreds or thousands of barriers, some of which no longer meet societal purposes. Accordingly, both conservationists and infrastructure managers are faced with the challenge of prioritizing barriers for repair, replacement, or removal. Candidate projects have been prioritized with dozens of methods, which span a wide range of spatial scales, data and analytical requirements, mathematical complexity, and capacity to reconcile multiple perspectives and objectives. We briefly review barrier prioritization methods from the perspective of a policy maker or manager who must balance realities of stochastic opportunities, conflicting priorities, and risk of infrastructure failure. After outlining common motivations for barrier prioritization, we present a menu of techniques ranging from large-scale, quantitative assessments to reactive, local response to failures. By clarifying the appropriate domain for each approach, this review informs the selection of prioritization methods for restoring riverine connectivity.

Panlasigui, S., Davis, A. J. S., Mangiante, M. J., & Darling, J. A. (2018). Assessing Threats of Non-Native Species to Native Freshwater Biodiversity: Conservation Priorities for the United States. *Biological Conservation,* 224, 199-208. https://doi.org/10.1016/j.biocon.2018.05.019

Non-native species pose one of the greatest threats to native biodiversity, and can have severe negative impacts in freshwater ecosystems. Identifying regions of spatial overlap between high freshwater biodiversity and high invasion pressure may thus better inform the prioritization of freshwater conservation efforts. We employ geospatial analysis of species distribution data to investigate the potential threat of non-native species to aquatic animal taxa across the continental United States. We mapped non-native aquatic plant and animal species richness and cumulative invasion pressure to estimate overall negative impact associated with species introductions. These distributions were compared to distributions of native aquatic animal taxa derived from the International Union for the Conservation of Nature (IUCN) database. To identify hotspots of native biodiversity we mapped total species richness, number of threatened and endangered species, and a community index of species rarity calculated at the watershed scale. An overall priority index allowed identification of watersheds experiencing high pressure from non-native species and also exhibiting high native biodiversity conservation value. While priority regions are roughly consistent with previously reported prioritization maps for the US, we also recognize novel priority areas characterized by moderate-to-high native diversity but extremely high invasion pressure. We further compared priority areas with existing conservation protections as well as projected future threats associated with land use change. Our findings suggest that many regions of elevated freshwater biodiversity value are compromised by high invasion pressure, and are poorly safeguarded by existing conservation mechanisms and are likely to experience significant additional stresses in the future.

Reynolds, K. M. (2001). Prioritizing Salmon Habitat Restoration with the Ahp, Smart, and Uncertain Data. In *The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making.* D. L. Schmoldt, J. Kangas, G. A. Mendoza, & M. Pesonen (Eds.), (pp. 199-217). Dordrecht: Springer Netherlands https://doi.org/10.1007/978-94-015-9799-9_13

Ecological assessments provide essential background information about ecosystem states and processes and are thus a useful starting point for applying adaptive ecosystem management. As a logical follow-up to ecological assessment, managers may wish to identify, and set priorities for, ecosystem maintenance and restoration activities. The Simple Multi-Attribute Rating Technique (SMART) is a useful extension to the standard AHP model that allows characterisation of uncertainty in attribute values of alternatives, and thus is one way of incorporating risk analysis into the standard AHP model. Criterium DecisionPlus is used to demonstrate application of the AHP and SMART methods to the problem of evaluating priorities for salmon habitat restoration projects.

Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., . . . Cooke, S. J. (2018). The Future of Fish Passage Science, Engineering, and Practice. *Fish and Fisheries,* 19(2), 340-362. https://doi.org/10.1111/faf.12258

Much effort has been devoted to developing, constructing and refining fish passage facilities to enable target species to pass barriers on fluvial systems, and yet, fishway science, engineering and practice remain imperfect. In this review, 17 experts from different fish passage research fields (i.e., biology, ecology, physiology, ecohydraulics, engineering) and from different continents (i.e., North and South America, Europe, Africa, Australia) identified knowledge gaps and provided a roadmap for research priorities and technical developments. Once dominated by an engineering-focused approach, fishway science today involves a wide range of disciplines from fish behaviour to socioeconomics to complex modelling of passage prioritization options in river networks. River barrier impacts on fish migration and dispersal are currently better understood than historically, but basic ecological knowledge underpinning the need for effective fish passage in many regions of the world, including in biodiversity hotspots (e.g., equatorial Africa, South-East Asia), remains largely unknown. Designing efficient fishways, with minimal passage delay and post-passage impacts, requires adaptive management and continued innovation. While the use of fishways in river restoration demands a transition towards fish passage at the community scale, advances in selective fishways are also needed to manage invasive fish colonization. Because of the erroneous view in some literature and communities of practice that fish passage is largely a proven technology, improved international collaboration, information sharing, method standardization and multidisciplinary training are needed. Further development of regional expertise is needed in South America, Asia and Africa where hydropower dams are currently being planned and constructed.

Thomas, G. (2014). Improving Restoration Practice by Deriving Appropriate Techniques from Analysing the Spatial Organization of River Networks. *Limnologica,* 45, 50-60. https://doi.org/10.1016/j.limno.2013.10.003

Amendments to the water protection legislation in many countries have raised the need to develop prioritization strategies in river restoration. These political objectives need to be translated into applied methods of site selection. The high degree of heterogeneity within administrative boundaries makes the

identification of sites challenging. Analysing data with computer software alone might not identify sites with the highest ecological recovery potential, as they might not take sufficient account of the complex ecological interplay over large spatial scales. In this literature study, the spatial organization of river networks (dendritic structure, unidirectional flow, species distribution) is discussed in the context of different restoration techniques and how efficiency is expected to vary within the network. Although restoration planning must consider deficits on the reach scale, as well as catchment effects and develop suitable mitigation scenarios produced by the analysis, some general conclusions on the site-specific effectiveness of different restoration techniques can be derived from the spatial organization of river networks. Restorations in the headwaters are most suitable for improving fundamental ecological processes such as retaining nutrients and soils to improve water quality, buffering an increase of temperature by establishing riparian buffer-strips, and returning hydro-dynamic flow patterns to a more natural state by altered dam operation. Longitudinal connectivity is essential for many freshwater taxa and should be restored in a bottom-up direction, starting at the downstream ends of river networks or at species-rich nodes within the system. Habitat restorations and the re-establishment of a natural channel morphology throughout the network will aid ecological recovery, if species pools for re-colonization are close by and fundamental ecological processes support a recovery. To increase the success of future restoration efforts, branches of river networks should be seen as functional linked ecosystems, and therefore restoration efforts within one system should be more coordinated, rather than seeing every project as self-sufficient. There must be a shift from a tactical towards a strategic approach in river restorations.

Tullos, D. D., Collins, M. J., Bellmore, J. R., Bountry, J. A., Connolly, P. J., Shafroth, P. B., & Wilcox, A. C. (2016). Synthesis of Common Management Concerns Associated with Dam Removal. *Journal of the American Water Resources Association,* 52(5), 1179-1206. https://doi.org/10.1111/1752-1688.12450

Managers make decisions regarding if and how to remove dams in spite of uncertainty surrounding physical and ecological responses, and stakeholders often raise concerns about certain negative effects, regardless of whether these concerns are warranted at a particular site. We used a dam-removal science database supplemented with other information sources to explore seven frequently raised concerns, herein Common Management Concerns (CMCs). We investigate the occurrence of these concerns and the contributing biophysical controls. The CMCs addressed are the following: degree and rate of reservoir sediment erosion, excessive channel incision upstream of reservoirs, downstream sediment aggradation, elevated downstream turbidity, drawdown impacts on local water infrastructure, colonization of reservoir sediments by nonnative plants, and expansion of invasive fish. Biophysical controls emerged for some of the concerns, providing managers with information to assess whether a given concern is likely to occur at a site. To fully assess CMC risk, managers should concurrently evaluate site conditions and identify the ecosystem or human uses that will be negatively affected if the biophysical phenomenon producing the CMC occurs. We show how many CMCs have one or more controls in common, facilitating the identification of multiple risks at a site, and demonstrate why CMC risks should be considered in the context of other factors such as natural watershed variability and disturbance history.

Section II: Other

Barbour, E. J., Holz, L., Kuczera, G., Pollino, C. A., Jakeman, A. J., & Loucks, D. P. (2016). Optimisation as a Process for Understanding and Managing River Ecosystems. *Environmental Modelling & Software,* 83, 167-178. https://doi.org/10.1016/j.envsoft.2016.04.029

Optimisation can assist in the management of riverine ecosystems through the exploration of multiple alternative management strategies, and the evaluation of trade-offs between conflicting objectives. In addition, it can facilitate communication and learning about the system. However, the effectiveness of optimisation in aiding decision making for ecological management is currently limited by four major challenges: identification and quantification of ecosystem objectives; representation of ecosystems in predictive simulation models; specification of objectives and management alternatives in an optimisation framework; and evaluation of model results against actual ecological outcomes. This study evaluates previous literature in ecology, optimisation and decision science, and provides a strategy for addressing the challenges identified. It highlights the need for better recognition and analysis of assumptions in optimisation modelling as part of a process that generates and shares knowledge. (C) 2016 Elsevier Ltd. All rights reserved.

Carwardine, J., Martin, T. G., Firn, J., Reyes, R. P., Nicol, S., Reeson, A., . . . Chades, I. (2019). Priority Threat Management for Biodiversity Conservation: A Handbook. *Journal of Applied Ecology,* 56(2), 481-490. https://doi.org/10.1111/1365-2664.13268

Threats to biodiversity and the integrity of ecological systems are escalating globally, both within and outside of protected areas. Decision makers have inadequate resources to manage all threats and typically lack information on the likely outcomes and cost-effectiveness of possible management strategies. Priority Threat Management (PTM) is an emerging approach designed to address this challenge, by defining and appraising cost-effective strategies for mitigating threats to biodiversity across regions. The scientific and practical impacts of PTM are increasing, with a growing number of case study applications across the globe. Here, we provide guidance and resource material for conducting the PTM process based on our experience delivering six large-scale projects across Australia and Canada. Our handbook describes the four stages of PTM: scoping and planning; defining and collecting key elements; analysing the cost-effectiveness of strategies; and communicating and integrating recommendations. We summarise critical tips, strengths, and limitations and scope for possible enhancements of the approach. Priority Threat Management harnesses scientific and expert-derived information to prioritise management strategies based on their benefit to biodiversity, management costs and feasibility. The approach involves collaboration with key experts and stakeholders in a region to improve knowledge sharing and conservation support. The PTM approach identifies sets of regional level strategies that together provide the greatest benefits for multiple species under a limited budget, which can be used to inform existing processes for decision-making. The PTM approach applies some generalisations in management strategies and resolution, in order to address complex challenges. Further developments of the approach include testing in a greater range of socioecological systems with adaptations that cater for multiobjective decisions. Synthesis and applications. Priority Threat Management is a decision science approach that brings people together to define and prioritise strategies for managing threats to biodiversity across broad regions. It delivers a prospectus for investment in the biodiversity of a region that is transparent, repeatable, participatory, and based on

the best available information. Our handbook provides the necessary guidance and resources for expanding the Priority Threat Management approach to new locations, contexts, and challenges.

Cattarino, L., Hermoso, V., Carwardine, J., Adams, V. M., Kennard, M. J., & Linke, S. (2018). Information Uncertainty Influences Conservation Outcomes When Prioritizing Multi-Action Management Efforts. *Journal of Applied Ecology,* 55(5), 2171-2180. https://doi.org/10.1111/1365-2664.13147

1. In managing various threats to biodiversity, it is important to prioritize multiple management actions and the levels of effort to apply. However, a spatial conservation prioritization framework that integrates these key aspects, and can be generalized, is still missing. Moreover, assessing the robustness of prioritization frameworks to uncertainty in species responses to management is critical to avoid misallocation of limited resources. Yet, the impact of information uncertainty on prioritization of management effort remains unknown. 2. We present an approach for prioritizing alternative levels of conservation management effort to multiple actions, based on the ecological responses of species to management. We estimated species responses through a structured email-based expert elicitation process, where we also captured the uncertainty in individual experts' assessments. We identified priority locations and associated level of management of effort of four actions to abate threats to freshwater-dependent fauna, using a northern Australia case study, and quantified sensitivity of the proposed solution to uncertainty in the answers of each individual expert. 3. Achievement of conservation targets for freshwater-dependent fauna in the Daly River catchment would require 9.4million AU$ per year, for a total of approximately 189 million AU$ investment over 20years. We suggest that this could be best achieved through a mix of aerial shooting of buffalos and pigs, riparian fencing and chemical spraying of weeds, applied at varying levels of management effort in key areas of the catchment. 4. Uncertainty in experts' estimation of species responses to threats causes 60% of the species to achieve 80% of their conservation targets, which was consistent across target levels.

Eros, T., O'Hanley, J. R., & Czegledi, I. (2018). A Unified Model for Optimizing Riverscape Conservation. *Journal of Applied Ecology,* 55(4), 1871-1883. https://doi.org/10.1111/1365-2664.13142

1. Spatial prioritization tools provide a means of finding efficient trade-offs between biodiversity protection and the delivery of ecosystem services. Although a large number of prioritization approaches have been proposed in the literature, most are specifically designed for terrestrial systems. When applied to river ecosystems, they often fail to adequately account for the essential role that landscape connectivity plays in maintaining both biodiversity and ecosystem services. This is particularly true of longitudinal connectivity, which in many river catchments is highly altered by the presence of dams, stream-road crossings, and other artificial structures. 2. We propose a novel framework for coordinating river conservation and connectivity restoration. As part of this, we formulate an optimization model for deciding which subcatchments to designate for ecosystem services and which to include in a river protected area (RPA) network, while also deciding which existing river barriers to remove in order to maximize longitudinal connectivity within the RPA network. In addition to constraints on the size and makeup of the RPA network, the model also considers the suitability of sites for conservation, based on a biological integrity index, and connectivity to multiple habitat types. We demonstrate the usefulness of our approach using a case study involving four managed river catchments located in Hungary. 3. Results show that large increases in connectivity-weighted habitat can be achieved through targeted

selection of barrier removals and that the benefits of barrier removal are strongly depend on RPA network size. We find that (i) highly suboptimal solutions are produced if habitat conservation planning and connectivity restoration are done separately and (ii) RPA acquisition provides substantially greater marginal benefits than barrier removal given limited resources. 4. Synthesis and applications. Finding a balance between conservation and ecosystem services provision should give more consideration to connectivity restoration planning, especially in multi-use riverscapes. We present the first modelling framework to directly integrate and optimize river conservation and connectivity restoration planning. This framework can help conservation managers to account better for connectivity, resulting in more effective catchment scale maintenance of biological integrity and ecosystem services delivery.

Game, E. T., Kareiva, P., & Possingham, H. P. (2013). Six Common Mistakes in Conservation Priority Setting. *Conservation Biology,* 27(3), 480-485. https://doi.org/10.1111/cobi.12051

A vast number of prioritization schemes have been developed to help conservation navigate tough decisions about the allocation of finite resources. However, the application of quantitative approaches to setting priorities in conservation frequently includes mistakes that can undermine their authors' intention to be more rigorous and scientific in the way priorities are established and resources allocated. Drawing on well-established principles of decision science, we highlight 6 mistakes commonly associated with setting priorities for conservation: not acknowledging conservation plans are prioritizations; trying to solve an ill-defined problem; not prioritizing actions; arbitrariness; hidden value judgments; and not acknowledging risk of failure. We explain these mistakes and offer a path to help conservation planners avoid making the same mistakes in future prioritizations.

Januchowski-Hartley, S. R., Visconti, P., & Pressey, R. L. (2011). A Systematic Approach for Prioritizing Multiple Management Actions for Invasive Species. *Biological Invasions,* 13(5), 1241-1253. https://doi.org/10.1007/s10530-011-9960-7

The successful management and eradication of invasive species is often constrained by insufficient or inconsistent funding. Consequently, managers are usually forced to select a subset of infested areas to manage. Further, managers may be unaware of the most effective methods for identifying priority areas and so are unable to maximize the effectiveness of their limited resources. To address these issues, we present a spatially explicit decision method that can be used to identify actions to manage invasive species while minimizing costs and the likelihood of reinvasion. We apply the method to a real-world management scenario, aimed at managing an invasive aquatic macrophyte, olive hymenachne (Hymenachne amplexicaulis), which is one of the most threatening invasives in tropical Australia, affecting water quality, freshwater biodiversity, and fisheries.

Le Berre, M., Noble, V., Pires, M., Medail, F., & Diadema, K. (2019). How to Hierarchise Species to Determine Priorities for Conservation Action? A Critical Analysis. *Biodiversity and Conservation,* 28(12), 3051-3071. https://doi.org/10.1007/s10531-019-01820-w

Hierarchisation and prioritisation methods represent a crucial step to determine priorities and implement actions in conservation biology: they are required to determine how to allocate available resources to the different components of biodiversity. However, they are very heterogeneous in terms of targets and goals. The main differences are presented with a focus on hierarchisation methods targeting species. This paper reviews 40 studies using 24 different point-scoring or rule-based methods aiming to determine conservation concerns for species. Only the hierarchisation methods targeting species were compared and their differences where highlighted in terms of study area, taxa, criteria assessment and summarisation. Then six different studies using the same hierarchisation method for species were compared as well. This study enables to analyse the different existing methods in order to perform more relevant methodological choices adapted to the objective and the context of each selection process. A consistent framework is designed to help managers to choose an appropriate method using well-defined goals, study areas and taxonomic targets, and take into account data availability.

Lin, H. Y., Robinson, K. F., Jones, M. L., & Walter, L. (2019). Using Structured Decision Making to Overcome Scale Mismatch Challenges in Barrier Removal for Watershed Restoration. *Fisheries,* 44(11), 545-550. https://doi.org/10.1002/fsh.10342

The removal of barriers, such as dams and culverts, has become a commonly used approach in river restoration to re-establish the connectivity of river flow, sediment, and species movement (Foley et al. 2017a). These removals have resulted in increases in native species richness, diversity, and productivity (Foley et al. 2017a). Barrier removal is also used to restore commercially important or threatened migratory fish, such as salmonids (family Salmonidae), alosines (family Clupeidae), sturgeons (family Acipenseridae), Sea Lamprey Petromyzon marinus, and freshwater eels Anguilla spp., by improving the connectivity between feeding and spawning habitats (Pess et al. 2014). Although more than 1,400 dams have been removed across America, Asia, Europe, and Australia (Duda et al. 2018), the decision to remove a barrier is usually influenced by objectives beyond restoring local ecosystems or fish populations (Fox et al. 2016). For example, regardless of ecological effects, many old dams in New England are preserved because of their historic value (Fox et al. 2016). Potential effects of barrier removals can occur at a variety of scales, which means that the consequences may be felt by diverse stakeholders, thus making decisions about removal all the more challenging (examples are provided in the following section and in Tables 1–3). Here, we examine these challenges, propose the framework of structured decision making (SDM) for addressing them, and test the potential of an applied SDM framework with decision makers and stakeholders in workshops.

Meng, B., Liu, J. L., Bao, K., & Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. *Integrated Environmental Assessment and Management,* 16(4), 438-451. https://doi.org/10.1002/ieam.4256

Under the dual influences of high-intensity anthropogenic activity and climate change, wetland hydrologic connectivity (HC) has decreased significantly, resulting in the severe fragmentation of

wetlands, a decrease in wetland area, and a degradation of hydrological functions, resulting in a worsening disaster response to floods and droughts. Dynamic changes in wetland HC are affected by a variety of factors. Many degraded wetlands have undergone measures to restore HC. Recovery can improve the HC pattern of degraded wetlands. Based on the knowledge of practitioners and a review of the literature, it was found that recovery measures can be divided into structural recovery and functional recovery according to the specific recovery objectives. However, the current recovery method lacks a holistic analysis of the HC pattern. To this end, we propose a hydrologic network-water balance-based HC recovery and management framework that overcomes the limitations of single-drive-factor repair and local repair effects. Integr Environ Assess Manag 2020;00:1-14. (c) 2020 SETAC

Travers, H., Selinske, M., Nuno, A., Serban, A., Mancini, F., Barychka, T., . . . Milner-Gulland, E. J. (2019). A Manifesto for Predictive Conservation. *Biological Conservation,* 237, 12-18. https://doi.org/10.1016/j.biocon.2019.05.059

If efforts to tackle biodiversity loss and its impact on human wellbeing are to be successful, conservation must learn from other fields which use predictive methods to foresee shocks and pre-empt their impacts in the face of uncertainty, such as military studies, public health and finance. Despite a long history of using predictive models to understand the dynamics of ecological systems and human disturbance, conservationists do not systematically apply predictive approaches when designing and implementing behavioural interventions. This is an important omission because human behaviour is the underlying cause of current widespread biodiversity loss. Here, we critically assess how predictive approaches can transform the way conservation scientists and practitioners plan for and implement social and behavioural change among people living with wildlife. Our manifesto for predictive conservation recognises that social-ecological systems are dynamic, uncertain and complex, and calls on conservationists to embrace the forward-thinking approach which effective conservation requires.