Garcia de Leaniz, Carlos and O'Hanley, Jesse (2021) ***Best practices for selecting barriers within European catchments.*** **Technical report. European Open Rivers Programme**

Best practices for selecting barriers within European catchments

Renival of Trefilerias dam
R. Gandara (Spain).

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September 3rd, 2021

Funding

This report was produced for The Nature Conservancy. It was funded with support from Arcadia, a charitable fund of Lisbet Rausing and Peter Baldwin

Disclaimer

The opinions and views expressed in this report are those of the authors and do not represent the views of the funder.

Quote

"Never give up; for even rivers someday wash dams away."
- Arthur Golden

Executive Summary

With over 1.2 million dams and other instream barriers, Europe has possibly the most fragmented rivers in the world, but also the opportunity to benefit enormously from barrier removal. Resources available for barrier removal, however, are limited and some form of prioritization strategy is thus required to select barriers for removal that will provide the greatest gains from restoring river connectivity in the most efficient possible way. To properly restore river function, barrier removal programs need to consider all types of artificial instream barriers that cause river fragmentation, not just those that impede fish movements.

Opportunities for barrier removal depend to a large extent on barrier typology, as this dictates not only where barriers are typically located, but also their size, age, condition, and impacts. Crucially, the extent of river fragmentation depends chiefly on the number and location of barriers, not on barrier size. However, because barrier removal costs typically increase with barrier height, acting on many small barriers may be more cost-efficient than acting on fewer larger structures.

Here we review the main strategies available to prioritize barriers for removal and mitigation, with special emphasis on removing non-ponding, low-head (<3 m) barriers, as these are the most abundant across Europe and other regions. To increase the success of barrier removal programs, we recommend that barriers considered for removal fulfill four essential conditions: (1) they would bring about a meaningful gain in connectivity; (2) are cost-effective to remove; (3) will not cause significant or lasting environmental damage, and (4) are obsolete structures.

There are dozens of prioritization methods in use. These can be broadly grouped into six main types depending on whether they are reactive or proactive, whether they are typically applied at local or larger spatial scales, and whether they employ an informal or a formal approach. These include, in increasing order of complexity: (1) opportunistic response; (2) use of local knowledge and expert opinion; (3) scoring and ranking; (4) geographic information system (GIS) scenario analysis; (5) graph theory; and (6) mathematical optimization. We review their strengths and weaknesses and provide examples of their use. Overall, mathematical optimization sets the gold standard for effective and robust barrier mitigation planning, but to be practical, it needs to factor in the constraints imposed by uncertainties and opportunities. Accordingly, a hybrid approach that considers uncertainty, the presence of natural barriers, the importance of future-proofing, and opportunities provided by local knowledge is likely to be the best overall approach to adopt.

Various studies have shown that a small proportion of barriers is typically responsible for the majority of river fragmentation. These 'fragmentizers' can be identified and located using the prioritization methods discussed herein and a targeted approach can produce substantial gains in connectivity by acting on a relatively small number of structures. Unfortunately, many of these 'fragmentizers' cannot be easily removed. Removal, therefore, is constrained by opportunities and what is practically feasible. Mapping of barrier removal projects according to the three axes of opportunities, costs, and gains can help locate the 'low hanging fruits.' Opportunities normally develop over time as infrastructure ages, so acting on some barriers now will likely open opportunities for acting on others later on to create a snowballing effect.

The ability to simulate benefits and costs of barrier removal and select barriers for removal is critically dependent the quality of the data at hand, particularly with respect to the number of barriers, which can be grossly underrepresented. Uncertainty caused by incomplete barrier records diminishes the effectiveness of barrier mitigation actions but these can be overcome to some extent by (1) ground truthing via river walkovers or (2) predictive modelling. Other critical sources of uncertainly include those caused by inaccurate stream networks and spatial errors regarding the exact locations of barriers. Although uncertainties can be reduced by collecting more information, it needs to be weighed against the cost of waiting. Waiting to

collect more data to reduce uncertainties tied to barrier removal may lead to 'paralysis by analysis,' while species and ecosystems continue to decline due to stream fragmentation.

To better understand how barrier prioritization is implemented in the real world, we sent out an online questionnaire to river restoration practitioners located in Europe and North America. Results show that most organizations (~60%) have a plan to achieve free-flowing rivers. Most respondents (34%) use expert judgment, followed by consultation with stakeholders (17%) and a combination of methods (28%) to prioritize barriers for mitigation. Only 12% used specialized software or algorithms. Attributes most frequently considered by practitioners in barrier prioritization were barrier ownership and rights, results of field surveys, and the obsolescence and conservation status of barriers. The most important rational flagged by practitioners to prioritize barriers for removal was to improve fish passage.

Our study suggests that no matter what prioritization approach is ultimately adopted, decision makers need to be mindful that no priorities should be set in stone. Planning needs to be agile and flexible enough to adapt to changes and react to opportunities.

1. What is a barrier?

A common misconception is that only barriers of a certain size fragment rivers and that migratory fish are the only taxa impacted by barriers. This is not the case. For example, many studies have shown that often river-road crossings, even those that have small head drops, can block or delay fish passage and that the smaller a stream is, the more likely it is that fish passage will be impeded (Diebel *et al.* 2015). Studies have also shown that weirs as small as 20 cm in height can impair the movement of weak swimmers (Jones *et al.* 2021) and that low head barriers can negatively impact macrophyte dispersal (Jones *et al.* 2020b). Therefore, although minimum height thresholds have often been used to identify fish barriers (typically >50 cm), there is not really a minimum barrier height that will avoid fragmentation. Instead it is more useful to view barriers by what they do rather, than by how big they are. Our definition of barrier follows that of Belletti *et al.* (2020): 'any built structure that interrupts or modifies the flow of water, the transport of sediments, or the movement of organisms and can cause longitudinal discontinuity.' Therefore, barriers that one may wish to prioritize for removal include not just those that affect fish dispersal, but also other river processes. In what follows, we take barriers to mean artificial physical structures that impair longitudinal connectivity. We exclude lateral and vertical barriers and also those that are not physical structures, for example thermal or pollution barriers.

2. Barrier typology and why it matters

The majority of barriers can be classified into six broad types, as suggested by Belletti *et al.* (2020), which differ based on key features and extent of habitat modification (Jones *et al.* 2020a) as shown in **Figure 1.**

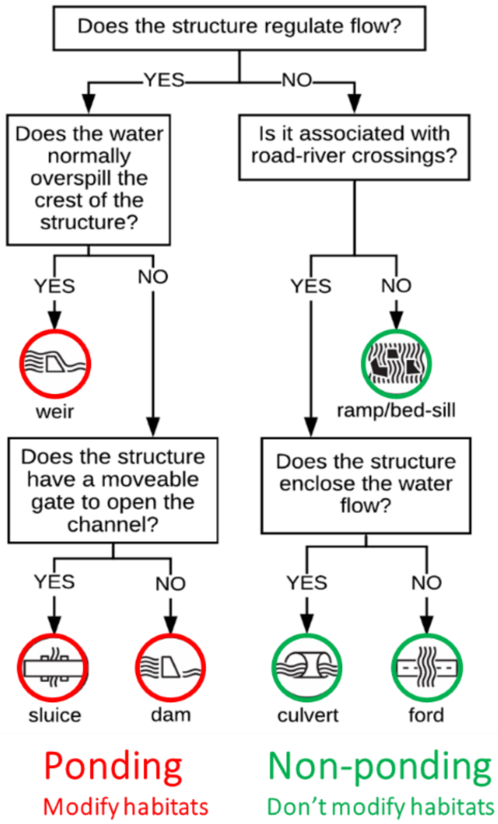

Figure 1. Classification of six main barrier types (Jones et al., 2020a).

Weirs and dams may be the most recognizable instream barriers, but they are not the only ones. Opportunities for barrier removal depend to a large extent on barrier typology, as this dictates where barriers are located in the catchment, as well as their size, age, condition and impacts (**Figure 2**). For example, many large dams in Europe were built in the 1950's and 60's and are getting closer to their design lifespan and possibly becoming unsafe, which will favor decommissioning. In contrast, culverts and bed-sills have typically been built more recently and for completely different purposes. Dams generally cause larger per capita impacts than other barrier types, including substantial ponding, but are relatively few in number so their effect on overall fragmentation is minimal. Further, their greater height makes their removal expensive, so the benefit-cost ratio is less attractive. In contrast, small structures like culverts, ramps and fords are mostly located in headwaters (Diebel *et al.* 2015; Neeson *et al.* 2018), are much more abundant (Belletti *et al.* 2020) and also easier and cheaper to remove.

However, they are less likely to be obsolete and removal may cause unacceptable loss of services or impacts on the environment, so mitigation or replacement (e.g., with a better structure of the same type or by another type of structure like a bridge) may be the only option. Clearly, to remove barriers sensibly, one needs to know how they differ and why they were built in the first place (**Figure 2**).

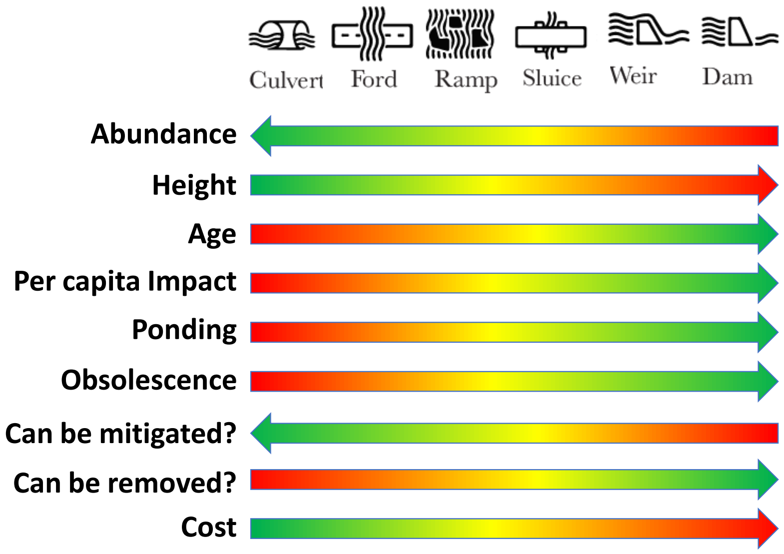

Figure 2. Characteristics of different barrier types and how these can affect decisions about barrier removal. The direction of arrows represent an increase in a given trait and the color the benefit or suitability of removal (note these are only indicative).

3. Why prioritize?

An underlying goal of most barrier mitigation programs is to maximize increases in reconnected habitat given available resources. Unfortunately, resources available for carrying out barrier mitigation work are usually quite limited. Because of this, some sort of prioritization process is normally required to efficiently target barrier mitigation actions, including repair, replacement, retrofitting and removal. All instream barriers cause some impacts, but because barrier impacts differ (**Figure 2**) and barriers are not evenly distributed within a catchment, the removal of certain barriers is more beneficial than the removal of others. Indeed, the removal of some barriers may not be beneficial at all if, for example, they allow the spread of aquatic invasive species, mobilize toxic sediments or help reconnect polluted waters, thus damaging good habitats by poor ones (Bednarek 2001; Stanley & Doyle 2003; Tullos *et al.* 2016). There is, therefore, a need to prioritize barriers whose removal should normally fulfill three conditions:

1. They would bring about a meaningful gain in connectivity;
2. Can be removed in a cost-efficient way;
3. Will not cause significant or lasting environmental damage.

Given that most barriers are still in use, one would also need to target barriers that also fulfill a fourth condition, namely (4) structures that are obsolete and no longer in use.

Death by a thousand cuts paradigm: implications for barrier removal

It is worth bearing in mind that the cumulative fragmentation impact of many small barriers is usually much greater than the impact of a few, larger structures (death by a thousand cuts paradigm). For example, 68% of barriers in Europe are less than 2 m in height and only 0.1% are large (> 15 m) dams (Belletti *et al.* 2020). The impact of barriers on river fragmentation depends chiefly on their number and location, not on their height. However, removal costs typically increase with barrier height (Heinz Center 2002; Neeson *et al.* 2018). This means that for a given budget, acting on many small barriers may be more cost-efficient – and bring about greater gains in connectivity – than acting on fewer larger structures.

4. What to prioritize? Targets of barrier removal

A primary goal of most prioritization methods is to increase the distribution and abundance of one or more target species, typically fish (O'Hanley, 2011; Segurado et al., 2013; Kuby et al., 2005; Branco et al., 2014; Ioannidou and O'Hanley, 2019). While this can help address the needs of particular species, these may change and conservation targets may shift. For example, the benefits of reconnecting a 30 km river reach may differ substantially if the target is a highly mobile or a more sedentary species, but may be the same for sediment transport or to maintain whole river processes. An alternative to taxa-driven targets is to reconnect good quality habitats, as opposed to extending the range of specific target species (Diebel *et al.* 2015). For example, O'Hanley (2011) sought to maximize the size of the single largest contiguous section of river unimpeded by artificial barriers, also referred to as total barrier-free length (Jones *et al.* 2019). Similarly, both Diebel *et al.* (2015) and Rodeles *et al.* (2019) developed connectivity indices that take habitat quality into account. Connecting good quality habitats is important to avoid ecological traps, for example caused by pollution or unfavorable temperatures. Here, predicted changes in water quality can be used as a useful metric for barrier prioritization (Guetz 2020).

5. How to prioritize?

5.1 Overview of barrier prioritization methods

There are dozens of different barrier prioritization methods, which will typically consider not just barrier removal but also other options, such as repairs and various forms of technical easement in relation to fish passage. These are reviewed by Kemp & O'Hanley (2010), King & O'Hanley (2016), McKay *et al.* (2017), McKay *et al.* (2020), and Moody *et al.* (2017), among others. In addition, there are at least 23 metrics of river fragmentation and 13 metrics of flow alteration that one could use to assess baseline conditions and predict the response of barrier removal (Jumani *et al.* 2020), so choosing a barrier removal prioritization method can be a daunting task (King *et al.* 2021). Barrier prioritization methods can be generally classified into six main families (**Table 1**; **Figure 3**), depending on whether they are reactive or proactive, whether they are typically applied at local or larger spatial scales, and whether they employ an informal or a formal approach (McKay *et al.* 2020; Weiter 2014). These include, in increasing order of complexity, opportunistic response (OR), local knowledge and expert opinion (LK), scoring and ranking (SR), geographic information system (GIS) scenario analysis, graph theory (GT) and mathematical optimization (MO).

Table 1. Characteristics of the six main types of barrier prioritization methods.

	Prioritization method					
Trait	**OR**	**LK**	**SR**	**GIS**	**GT**	**MO**
Factor uncertainty	L	L	L	L	L	H
Difficulty	L	L	M	M	M	H
Flexibility	L	M	H	M	M	H
Optimal solution	L	L	L	M	M	H
Multiple objectives	L	L	L	M	M	H
Transparency	H	L	L	M	M	H
Repeatability	L	L	H	M	M	H
Multiple barriers	L	L	L	M	M	H
Stakeholder	M	H	M	L	L	L
Examples	American Rivers (2021)	Fox *et al.* (2016) Sneddon *et al.* (2017)	Roni *et al.* (2002) WDFW (2000)	Barrios (2011)	Cote *et al.* (2009) Segurado *et al.* (2013)	O'Hanley & Tomberlin (2005) Kuby *et al.* (2005)

Prioritization methods can also be broadly categorized into informal and formal (**Table 2**). Informal methods are the most widely used approach, particularly outside North America. They are distinguished by their qualitative nature and include both opportunistic response and expert judgement. Formal methods, in contrast, employ some sort of structured, quantitative analysis in which each criterion for prioritizing barriers must be explicitly defined and measured. Each approach has strengths and weaknesses and no method is best under all conditions (McKay *et al.* 2020). These are briefly discussed below.

Table 2. Cross comparison of common informal and formal barrier prioritization methods (partially adapted from McKay *et al.* (2020).

Prioritization Method	Strengths	Weaknesses	Objective	Coordinated	Efficient
Informal Methods					
Opportunistic response	• Few planning constraints to take into consideration. • Potential for a large number of projects to be implemented.	• Inefficient use of limited resources. • Potentially negligible gains in river connectivity.	Yes	No	No
Expert judgment	• Easy to assimilate domain knowledge from multiple disciplines (e.g., biology, hydrology, transportation, energy) • Flexibility in combining multiple environmental, economic and social criteria. • Little or no mathematical and programing expertise required.	• Requires substantial local knowledge. • Generally unmanageable at large spatial scales • Lacks rigor, highly subjective. • Can introduce bias (e.g., a priori preferences, disciplinary viewpoints).	No	Potentially	No
Formal Methods					
Scoring & ranking	• Easy to integrate multiple objectives, even those that are hard to quantify. • *Prescriptive* approach – provides a recommended course of action. • Minimal mathematical and programing expertise required.	• Usually ignores the spatial structure of barrier networks (e.g., impassable downstream barriers). • Mitigation decisions made independently, thus disregarding the interactive effects of barrier mitigation on river connectivity. • Can produce highly inefficient solutions.	Yes	No	No
GIS scenario analysis	• Visually appealing and easy to communicate findings. • Easy to scale up. • Able to handle many data layers.	• Highly subjective and lacks transparency. • *Descriptive* approach – provides no guidance on how to cost-efficiently mitigate barriers. • Requires requisite GIS expertise.			
Graph theory	• Designed to account for barrier spatial structure and the interactive effects of barrier mitigation on river connectivity. • Can be tailored to different fish life-history and dispersal patterns. • Potentially easier than optimization to align with planning constraints.	• *Descriptive* approach – provides no guidance on how to cost-efficiently mitigate barriers. • Only designed to do simple "what-if" type analyses focused on river connectivity enhancement. • Moderate level of mathematical and programing expertise required.	Yes	Yes	No
Mathematical optimization	• Designed to account for barrier spatial structure and the interactive effects of barrier mitigation on river connectivity. • Can be tailored to different fish life-history and dispersal patterns. • Highly objective and systematic approach to decision making. • Capable of balancing multiple, possibly competing, objectives and constraints. • *Prescriptive* approach – provides a recommended course of action. • Guaranteed to be cost-efficient.	• Solutions may require cooperation of multiple barrier owners, which may or may not be easy to achieve. • Changes to budgets and project costs can have a substantial impact on priorities. • Challenging to account for factors not easily quantifiable. • In general, solution quality heavily reliant on availability of complete and accurate data. • High level of mathematical and programing expertise required.	Yes	Yes	Yes

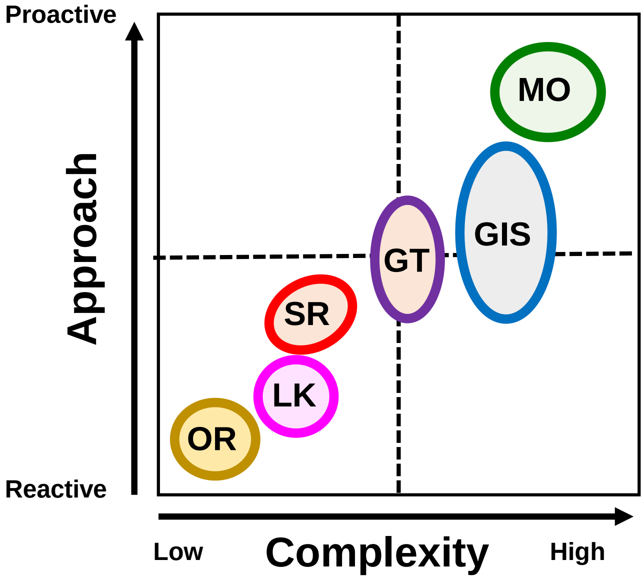

Figure 3. Classification of the main barrier prioritization methods according to their complexity and type of approach. OR - opportunistic response; LK - local knowledge & expert opinion; SR - scoring and ranking; GIS - GIS scenario analysis; GT - graph theory; MO - mathematical optimization.

5.1.1 Informal methods

Opportunistic response

Opportunistic response, also called reactive response (McKay *et al.* 2020), relies on a very simple strategy of mitigating barriers as and when opportunities arise, often in response to barrier owners seeking to remove older, legacy structures. Opportunistic response is a mostly passive strategy that has the benefit of requiring little or no strategic forward planning, thus eliminating analytical challenges and potentially facilitating the removal of more barriers than would otherwise be feasible due to lower logistical hurdles. American Rivers, for example, has removed dozens of dams in the US by identifying and working with owners of aging dams at risk of failure. A core assumption of opportunistic response is that any given barrier removal will result in river connectivity improvements. While this may often be true for resident fish and aquatic species, the extent to which long distance migratory fish, including diadromous salmon, will benefit largely depends on where a dam is located relative to other barriers. Removing a dam above of an impassable barrier located downstream will provide no connectivity gain for migratory species, even if the project is readily feasible. Accordingly, opportunistic response has the potential to be extremely inefficient if followed indiscriminately without taking into account important contextual considerations.

To avoid inefficiency, it is recommended that guidelines be adopted to ensure some minimal return on investment (McKay *et al.* 2020). For example, a river conservation organization could decide to focus efforts on minimally degraded rivers or employ a simple rule-of-thumb of first removing barriers closest to the river mouth. Basic standards such as these can help ensure an organization maintains an emphasis on delivering positive outcomes rather than jumping at every opportunity that comes along. On the other hand, as barriers tend to be spatially clustered, the removal of an opportunistic barrier that may not in itself result in a large return on investment may help rally support for the removal of other neighboring barriers that do.

Local knowledge & expert opinion

For this approach, barrier prioritization is based on using local knowledge about barriers together with together with input of experts from various fields of domain (e.g., biology, hydrology, engineering, transportation) to produce a short-list of barriers that are deemed to be most adversely impacting fish dispersal or environmental status within a given planning area. Criteria taken into consideration vary but often include the potential amount of habitat gained from mitigation, the type and relative quality of habitat made available for different species and or life-stages (e.g., rearing for juveniles versus breading habitat for adults), the potential spread of invasive species, and the presence/absence of downstream barriers. An advantage of this method is that it is easy to implement and captures knowledge and experience that can be difficult to formalize and use in any other way. It allows for extensive involvement of stakeholders, for example through public consultation, which can help reduce conflict over barrier decisions (Fox *et al.* 2016; Sneddon *et al.* 2017). A key weakness lies in its subjectivity and potential bias. For example, consultation may give undue weight to those that express the strongest opinions and decisions may be difficult to justify to funders. It also does not easily factor in uncertainty and cannot deal (at least explicitly) with trade-offs among multiple objectives. The process is not readily repeatable and, therefore, not transparent. Further, there is also no guarantee that the recommendation is cost-efficient.

In spite of its limitations, expert judgment is usually acceptable for identifying a core set of barriers to mitigate within a specific catchment that would yield the greatest overall gain (however ill-defined that may be). Where it critically fails is when applied to large spatial scales. Looking at multiple catchments simultaneously is generally far too difficult a task since local experts from each catchment need to be involved. Even when the problem is broken down by catchment, it becomes all but impossible to compare priorities across catchments and, in turn, allocate funding. A good example of the difficulty of employing expert judgement comes from the UK. The Environment Agency, which has statutory responsibility for maintaining environmental quality of English and Welsh freshwater bodies including free passage for migratory fish, employs a “divide-and-conquer” approach when it comes to barrier prioritization. The strategy relies on delegating responsibility to each region (7 in total) to come up with a list of high priority barriers for its jurisdiction. The manner in which priorities are arrived at are left to the individual regions and do not conform to a common set of criteria. To compound the problem, there are multiple species of interest across the different regions with each region focusing, to a greater or less extent, on a particular species or group of species. National level priorities are ultimately derived by “filtering” the various regional priorities using an ad-hoc process. This illustrates why expert judgement should generally be avoided when working at supra-basin scales.

5.1.2 Formal methods

Scoring & ranking

Scoring and ranking, without a doubt, is the most common type of formal method used for prioritizing barrier mitigation decisions (Kocovsky *et al.* 2009; Martin 2019; Martin & Apse 2011; Nunn & Cowx 2012; Taylor & Love 2003; WDFW 2009). As the name implies, barriers are scored according to a set of assessment criteria, ranked in order of score, and then selected for repair/removal based on rank until the budget is exhausted. Scoring systems typically account for one or more of the following: (i) habitat quantity; (ii) habitat quality; (iii) degree of improvement in fish passage as a result of mitigation; and (iv) cost of mitigation. More sophisticated ones (Martin 2019; Martin & Apse 2011; Nunn & Cowx 2012) further account for the number and or passability of downstream barriers, and can also deal with uncertainty. A widely employed scoring and ranking approach is to use benefit-cost ratios, namely habitat gain divided by costs of removal, with barriers then ranked from most to least cost-effective.

The appeal of scoring and ranking lies in its simplicity. Once barrier attributes and weightings have been agreed upon, the results are simple to communicate and decisions easy to explain. It is also flexible in that new attributes can be added or modified as more data become available. The main disadvantage is that barriers are treated independently from each other, without taking into account their spatial relationship, and as number of studies have shown (O'Hanley *et al.* 2013; O’Hanley & Tomberlin 2005) this often produces poor quality solutions. Cumulative passability (the degree to which fish and other aquatic organism can successfully pass multiple barriers arranged in series) is invariably determined by the passability of barriers downstream and upstream. Ignoring this can result in proposals to mitigate barriers located above impassable downstream barriers even though this would produce no habitat gain whatsoever.

While more elaborate scoring systems are able to take into account barrier spatial structure, scoring and ranking nonetheless suffers from an even more fundamental shortcoming, which is that decisions are made independently rather than in a coordinated manner. Scores are calculated assuming that passabilities at other barriers are constant. Mitigation of multiple barriers, however, produces non-additive or interactive changes in cumulative passability. Put another way, the gain produced by mitigating a particular barrier is not fixed; it depends on if and to what degree other barriers downstream or upstream have already been mitigated or are provisionally slated for mitigation. For this reason it not possible to find an optimal solution, as it cannot deal with multiple objectives or multiple barriers at once. In addition, stakeholder involvement is limited, although their opinions can be used to set the weightings and find the barrier attributes of choice. There is also no explicit consideration of uncertainty.

GIS scenario analysis

With GIS scenario analysis, various data layers and attributes are used as filters in a geographic information system (sometimes web-based) to simulate the consequences of acting on individual barriers or groups of them, typically by calculating very simple connectivity metrics like total reconnected stream distance in upstream and or downstream directions Barrios (2011). This information can then be used to produce a ranked list of single barrier interventions or a portfolio of barriers under different budget scenarios. This method is visually appealing, easy to communicate and can be very effective in conveying gains under various what-if budget scenarios (or other constraints). It is easy to scale up and can easily handle many data layers, many of which may be publicly available. The limitations of this approach is that it requires a GIS platform and appropriate expertise. It is sometimes limited to small spatial domains involving a limited number of barriers due to the extent of coverage provided by the data layers and that there may be limited stakeholder involvement if the implementation is not user-friendly or easily accessible online. Also, the choice of attributes to use or consider can be very subjective, which hampers repeatability and transparency. As with all other prioritization methods, apart from optimization, there is no way of knowing whether a particular barrier mitigation solution is cost-efficient.

Graph theory

Graph theory models overcome many of the limitations of scoring-and-ranking by capturing the dendritic structure of rivers and spatial relationships of barrier networks. In this way, they are able to account for the interactive effects of barrier mitigation on cumulative passability. The application of graph theory involves two, interlinked steps. First, a graph composed of nodes and arcs is created to represent a particular barrier network. Second, a numerical index of some kind is calculated to measure the overall degree of connectivity within a river network, thus making graph theory decidedly more sophisticated than ad hoc GIS scenario analysis. Different indices have been devised to suit specific fish dispersal and life-history needs, including diadromous and potadromous fish.

One of the first and most well-known graph theory models developed for barrier mitigation planning is the Dendritic Connectivity Index (DCI) proposed by Cote *et al.* (2009). To calculate DCI, a graph is constructed with barriers represented by nodes and arcs connecting adjacent barriers. Other graph theoretic approaches include work by Erős *et al.* (2011) and Segurado *et al.* (2013). The graph representation used by these authors is distinctly different from DCI in that nodes represent stream segments, while arcs designate whether or not stream segments are confluent with one another. Two widely used indices for this alternative graph representation are the Betweenness Centrality (BC) index and the Index of Connectivity (IIC). BC measures the frequency with which a node (stream segment) falls within the shortest path between pairs of nodes (stream segments) in a network. It attempts to quantify the role steam segments serve as a “stepping stones.” ICC, in contrast, provides an overall measure of longitudinal connectivity and quantifies the importance of both habitat availability and connectivity. For both BC and ICC, it is assumed that barriers are either complete passable or completely impassable. This makes these indices much more limited than DCI in that they do not allow for partial barrier passability.

Graph theory models are noteworthy for taking a holistic view of river connectivity. Unlike with scoring and ranking, they are specifically designed to incorporate the interactive effects of barrier mitigation, thus allowing decisions to be made in a coordinated manner. Nonetheless, graph theory models by themselves are merely *descriptive* – they do not provide any guidance as to how barriers can be mitigated in a cost-efficient manner. This makes them only useful for carrying out simple what-if type analyses (similar to GIS scenario analysis) involving questions like: How would longitudinal connectivity be affected by the mitigation of this particular barrier or this set of barriers? For a given budget, it is entirely up to the end-user to come up with a feasible portfolio of mitigation actions that maximizes overall connectivity.

Mathematical optimization

The final and most sophisticated barrier prioritization method is mathematical optimization, developed mostly over the last two decades (King & O'Hanley 2016; King *et al.* 2021; King *et al.* 2017; Kuby *et al.* 2005; Milt *et al.* 2018; Moody *et al.* 2017; O'Hanley 2011; O'Hanley *et al.* 2013; O'Hanley & Tomberlin 2005). Unlike other methods, which are generally descriptive, mathematical optimization is a prescriptive approach that produces a recommended course of action. Like graph theory, optimization is fully capable of accounting for the spatial structure of barrier networks and the interactive effects of mitigation on river connectivity. Optimization goes beyond graph theory, however, in being able to find an optimal or near optimal portfolio of barrier removals to maximize longitudinal connectivity gains subject to various constraints (e.g., a limited budget). In short, optimization ensures the best possible use of limited resources.

The use of optimization has other advantages as well (Kemp & O'Hanley 2010). The fact that they rely on clear and objective criteria makes them more transparent and repeatable. They also provide enormous flexibility by enabling decision makers to balance multiple, possibly competing, environmental and socioeconomic goals, like hydropower (Kuby *et al.* 2005), ecosystem productivity (Zheng *et al.* 2009), dam safety (Zheng & Hobbs 2013), fish abundance and richness (King *et al.* 2021), recreation (Roy *et al.* 2018), potential threats from invasive species (Milt *et al.* 2018), and climate change impacts (Farzaneh *et al.* 2021). Even uncertainty can be incorporated into an optimization model in a coherent fashion, allowing planners to effectively hedge against risk, including data limitation related to the number and location of barriers (Ioannidou *et al.* 2021).

Besides being useful for strategically targeting high impact barriers within a given area that yield the "biggest bang for the buck," optimization models can also be used in a variety of other ways. For example, connectivity gain versus barrier mitigation cost generally shows a pattern of diminishing return (King & O'Hanley 2016; O'Hanley 2011), whereby increases in connectivity become progressively smaller with increased budget and eventually reach a plateau. Habitat gain versus cost curves, however, are not always smooth; there may be critical thresholds, below which connectivity gains may be small. Accordingly, optimization can be helpful in identify appropriate levels of investment in barrier mitigation that are sufficient in meeting defined planning goals. At the very least, optimization models are useful for identifying potentially cost-efficient solutions that can form the basis for more detailed modeling and fine-tuning later on.

Optimization, however, is not without drawbacks. They can be viewed as excessively prescriptive (McKay *et al.* 2020) and tend to ignore local knowledge (Fox *et al.* 2016), which may antagonize some stakeholders (Sneddon *et al.* 2017) and make communication of results difficult. They also require a high degree of mathematical and computer programing expertise, although open source spatial planning software, such as MARXAN (Hermoso et al., 2021), and special purpose decision support tools, such as the Windows based OptiPass (O'Hanley 2014) and the Excel-based River Infrastructure Planning (RIP) tool[1,2] have recently been developed which should facilitate mainstreaming for some barrier removal programs. Other downsides include (1) the fact that small changes to budgets and project cost can result in markedly different solutions since there is no guarantee that solutions will be nested (O'Hanley 2011); (2) that the quality of solutions tends to be heavily reliant on the availability of complete and accurate barrier data; and (3) that recommended solutions may require cooperation of multiple barrier owners, which may or may not be easy to achieve. The latter two criticisms generally apply to all prioritization methods. Others have also argued that optimization may give a false impression of accuracy that simply does not exist in real life projects. For example, an optimal portfolio of barriers to be removed will no longer be 'optimal' if one or more of the selected barriers cannot be removed.

Regarding the issue of nestedness, this refers to the fact that barriers selected for removal at one budget may not be selected at a higher budget. The reason for this is that previously unaffordable or costly mitigation actions may suddenly become much more attractive only when the budget is sufficiently high. A single large expenditure may be more efficient than 'toping-up' annual budgets totaling the same amount (Neeson *et al.* 2015). There is also a tendency to favour the less expensive projects, which makes it important to run optimization models across multiple budget scenarios. King & O'Hanley (2016) found that optimal solutions generally selected barriers located in the lower part of the catchment (i.e., with more total upstream habitat). Others, however, have found that selected barriers are more frequently located in the middle part of the catchment (King *et al.* 2017; Kuby *et al.* 2005; O'Hanley 2011), although this probably varies depending on the type of river and the targeted species (e.g., diadromous vs. potadromous).

Taken together, optimization sets the gold standard for effective and robust barrier mitigation planning. But to be practical, it needs to factor in the constraints imposed by uncertainties and opportunities. A hybrid system is, therefore, probably best.

5.2 Prioritizing for barrier removal vs prioritizing for barrier mitigation

One fundamental aspect of some river restoration programs is that funding may only be available for barrier removal and may exclude other barrier mitigation alternatives, such as construction of fish passes, reconnection of side channels or culvert replacement. For example, the European Open Rivers Programme (EORP) has recently set aside €42.5 million over six years specifically to remove physical barriers, not to build fish passes or embark on other mitigating actions. Likewise, with its new Biodiversity Strategy, the European Commission has the vision to reconnect 25,000 km of free flowing rivers by 2030 and it is thought that this will be achieved primarily by targeting barriers for removal. Similarly, American Rivers, WWF, Dam Removal Europe and other organizations and collaborative initiatives emphasize barrier removal, not just in a figurative sense, but in a literal one (WWF 2021). This needs to be incorporated into the prioritization strategy, as not all barriers can necessarily be acted upon, only those that can be removed. Therefore, the baseline situation is not the white canvass implicit in most barrier prioritization exercises that aim to maximize connectivity in the most efficient possible way, but one where there is only a small subset of obsolete barriers that can be readily removed. Pilot data from Europe suggest that obsolete barriers represent ~13% of all barriers, which may considerably simplify the search for workable solutions, but also needs to be taken into account in the barrier prioritization process. As depicted in **Figure 2**, most non-flow regulating barriers cannot normally be removed, they can only be modified or replaced by something else, like a bridge in the case of a culvert,

[1] https://amber.international/software/
[2] https://amber.international/wp-content/uploads/2020/11/AMBER-Policy-Brief-2.pdf

which will incur additional costs and may rule them out from funding for barrier removal schemes.

5.3 Identifying the 'fragmentizers'

Instream barriers are not distributed at random, they tend to be clustered. This means that their impact on stream fragmentation is less than one would expect if they were distributed regularly or randomly (Diebel *et al.* 2015), but it also that most fragmentation is caused by a small proportion of barriers, the so called 'fragmentizers.' Fragmentizers can be identified and located using some of the prioritization methods outlined above and a targeted approach can produce substantial gains in connectivity by acting on a relatively small number of barriers (**Figure 4**). For example, in the Willamette River, USA, removing 8% of barriers would reconnect 52% of the basin (Kuby *et al.* 2005), while in the Afan catchment, Wales, 5% of barriers cause 50% of fragmentation (Jones et al., *in prep*.). Several studies have shown that the removal of some key barriers can result in disproportionately high gains in connectivity (Hermoso *et al.* 2021), but that benefits eventually top out (O'Hanley *et al.* 2013).

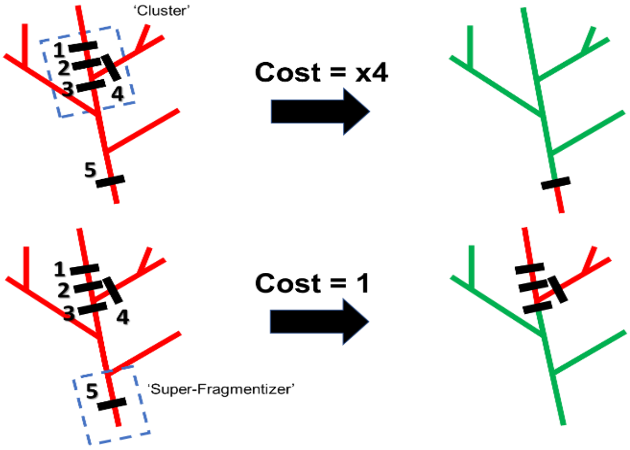

Figure 4. Stream barriers are not randomly distributed, they tend to be found in clusters (barriers 1-4). Acting on clusters will not normally yield significant gains, unless all barriers in a cluster are mitigated or removed (top). However, acting on some isolated barriers such as barrier 5 (a 'fragmentizer', bottom) may bring about large gains in connectivity and be more cost-effective. These barriers can be identified and removed, or be included in a strategic portfolio when the opportunity for removal arises.

5.4 Locating the low-hanging fruit and capitalizing on opportunities

Unfortunately, most barriers cannot be easily removed. This means that opportunities need to be factored into the barrier prioritization process, particularly if mitigation is not an option. The role of opportunism has seldom been considered explicitly, although it is recognized that it can play a vital role in prioritizing barriers for removal (Weiter 2014; Weiter 2015), particularly when uncertainty is high.

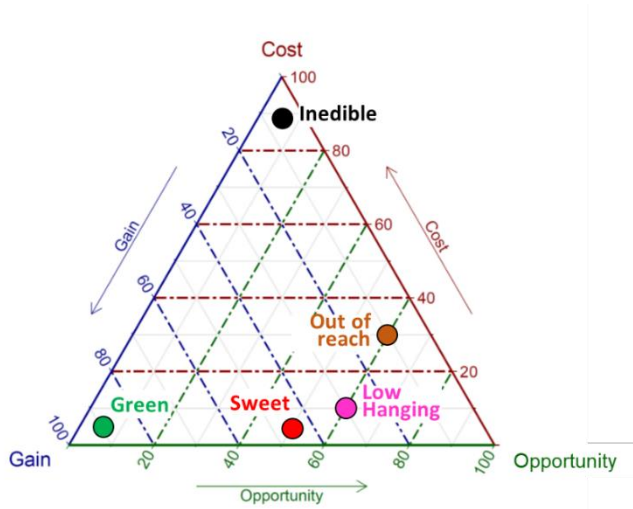

Figure 5. Mapping of barrier removal projects according to opportunities, cost and gains can help locate the 'low hanging fruit'. Projects that produce limited gains are regarded as 'inedible', regardless of what the opportunity or costs might be. Projects that can achieve high connectivity gains at low costs may be 'green' if the opportunity for removal is not quite there; these may ripen into 'sweet' fruit with time and stakeholder pressure. Some projects could produce substantial gains but they are too expensive and therefore are 'out of reach'. Only barriers that can readily be removed and that can be expected to produce significant connectivity gains at low cost are viewed as 'low hanging fruit'.

Barrier removal projects can be mapped into the three axes – opportunity, cost and gains – and this can help locate 'low hanging fruit' (**Figure 5**). Just as gains change depending on the interactive effects of multiple barriers, so do opportunities. Opportunities will develop over time as infrastructure ages and requires repair, replacement or decommissioning (Neeson *et al.* 2018), but also as support for barrier removal grows (WWF 2021). A snowballing effect should be expected with barrier removal at the catchment scale because acting on some initial barriers will likely open opportunities for acting on others.

5.5 Dealing with uncertainty

Uncertainty abounds in river restoration and planning, including restoration of connectivity. The benefits accrued from any individual barrier removal can be estimated but are rarely precise. Costs of barrier mitigation can be determined with a fair degree of accuracy but are heavily site dependent. Various studies have shown that having accurate costs is essential (Weiter 2015), but this is difficult when only a small proportion of barriers is surveyed, typically <5% (Weiter 2015). Consequently, when working at large spatial scales, one is invariably required to rely on rule-based or statistical cost models for approximating removal cost based on barrier type, size, and other physical characteristics. The same is true for estimating the passability of structures by different species or the efficiency of proposed fish passage solutions. Rarely are considerations about climate change taken into account in the barrier prioritization process, despite the fact that climate can have important implications for river connectivity. For example, river habitats made accessible through barrier removal now may no longer be suitable in the future due to changes in flow or temperature, which calls for considerations of future-proofing. Dam removal has also the potential to either increase or decrease carbon sequestration, affecting CH_4 and other carbon-based emissions locked in reservoir sediments (Maavara *et al.* 2020), which could have implications for climate change (Maavara *et al.* 2017).

Understanding the assumptions and limitations of different prioritization models is also important. The ability to simulate the gains and costs of barrier removal is critically dependent on the quality of the data at hand, particularly with respect to the number of barriers, which can be massively underrepresented (Belletti *et al.* 2020). Uncertainties caused by data gaps in barrier inventories are particularly problematic, because for every barrier recorded there may be another one missing (Belletti *et al.* 2020; Jones *et al.* 2019). Unrecorded barriers diminish the effectiveness of barrier mitigation actions and the possibility that it may not be practically or logistically feasible (now or in the future) to remove certain priority barriers limits what gains can be achieved and or necessitates revision of priorities. In practical terms, two ways that can be used to reduce uncertainties caused by incomplete barrier records is to (1) ground-truth via river walkovers and derive field corrected barrier densities (Atkinson *et al.* 2020; Belletti *et al.* 2020; Jones *et al.* 2019) and (2) predict the location of missing barriers using machine learning (Belletti *et al.* 2020; Januchowski-Hartley *et al.* 2021; Januchowski-Hartley *et al.* 2019; Jones *et al.* 2020a) or other predictive models.

Some metrics of connectivity require accurate barrier coordinates and this can be further compounded by inaccurate stream networks. For example, the only stream network available at a pan-European scale (ECRINS) may underestimate stream length by a factor of 3 because first and second order streams are poorly mapped (Kristensen & Globevnik 2014). There are also uncertainties about precise barrier locations, which can introduce important errors when 'snapping' them onto an already coarse river network.

Barrier removal planning must also contend with uncertainties related to the potential spread of invasive species and with future demands for water resources. Many would argue that the answer to resolving issues around uncertainty is to wait and gather more data before making a decision. Waiting for more information, however, involves its own opportunity costs (Grantham *et al.* 2009) and can lead to a 'paralysis by analysis' syndrome (Blanco 2008).

Acquiring new data is often costly and time consuming; money spent on data collection could alternatively be spent on further on-the-ground mitigation work. One also needs to consider that while data are being gathered, species and ecosystems may continue to decline due to stream fragmentation. Freshwater migratory fish have suffered a 93% decline in Europe over the last 45 years, due in large part to increasing fragmentation (Deinet *et al.* 2020), so waiting to collect more data to reduce uncertainties in river restoration may not be an option due to the irreparable harm that may be caused.

In the context of decision making, the benefits of investing in data gathering should be evaluated in terms of its potential to alter priorities and boost restoration gains, not simply to refine inputs and build better models. Here, value of information analysis might help with this challenge by rigorously examining trade-offs between the cost and benefits of gathering additional data (Maxwell *et al.* 2015). More fundamentally, we would argue that the best way to deal with uncertainty in the context of barrier prioritization and planning is to embrace uncertainty. Such an approach would encourage river restoration managers to: (1) explore in greater depth the extent and potential significance of uncertainties; (2) communicate uncertainties more effectively; and (3) adopt more flexible and adaptive strategies to cope with uncertainty.

More adaptive planning, in particular, would go a long way toward hedging risks while at the same time equip planners to take advantage of any opportunities that may arise to achieve easy wins that align with overall objectives. In part, some of this can and should be embedded within more robust prioritization tools and analysis procedures, which will require more work and development. But our point is a larger one than that. No matter what prioritization approach is ultimately adopted, decision makers need to be mindful that no priorities should be set in stone. Change and the unexpected, both bad and good, are sometimes forced upon even the most carefully laid plans. Planning needs to be ever agile and flexible enough to adapt.

5.6 The importance of considering natural barriers

Few studies account for the location of natural barriers (i.e., falls) despite the fact that these can have a dramatic effect on the optimal selection of barriers for removal (Diebel *et al.* 2015). In general, the benefits of acting on barriers located in the headwaters are lessened by their proximity to natural fragmented habitats and the smaller length of any upstream gains. While this may not matter for sediment transport or whole-river processes, natural features affect the distribution of fish species and what can be gained by barrier removal. Most barrier prioritization studies lack information on natural barriers and even when they do, it is assumed that they have no effect on connectivity (O'Hanley 2011), which may not be the case. For example, species richness typically decreases as one moves upstream within a river network, while natural fragmentation increases (Vannote *et al.* 1980), so the benefits of acting on headwater infrastructures may lessen. Missing information on the location of natural barriers can, to some extent, be overcome by considering channel slope, as steep gradients are typically unsuitable for many fish species. Gradient thresholds for migratory salmonids, for example, typically range between 2% and 16% (Finn *et al.* 2021; Hendry & Cragg-Hine 2003) and are much lower for weaker swimmers (Legalle *et al.* 2005).

5.7 Future-proofing barrier removal and the 'do-nothing' option

All barriers have a finite live span and proper maintenance is essential but also costly (Neeson *et al.* 2015). Opportunities presented by barrier obsolescence must be weighed against the alternative of the do-nothing option and the likelihood of structural failure. Under a scenario of more extreme weather events, investing in removing derelict or partially breached structures may not always be cost-effective if it merely brings the process forward by a few years. There is, therefore, a need to future-proof interventions.

Future-proofing barrier removal is also important in the face of climate change because the impact of barriers for species depends on future water levels and river flows. The impact of some barriers will worsen in countries where climate will get drier and flows are expected to decrease (e.g. Southern Europe, the Balkans) but will lessen in places expected to become wetter (e.g. Scandinavia - (Garcia de Leaniz *et al.* 2021).

6. Barrier prioritization in practice: Results from a questionnaire

An online questionnaire consisting of 6 questions was developed with *SurveyMonkey* and sent by email between June and July 2021 to ~200 river restoration practitioners (drawn from our networks and a list of registered attendees to previous webinars) across Europe and North America. A total of 58 responses were received by July 20th, representing a ~29% response rate across 14 European countries and the USA (**Figure 6**).

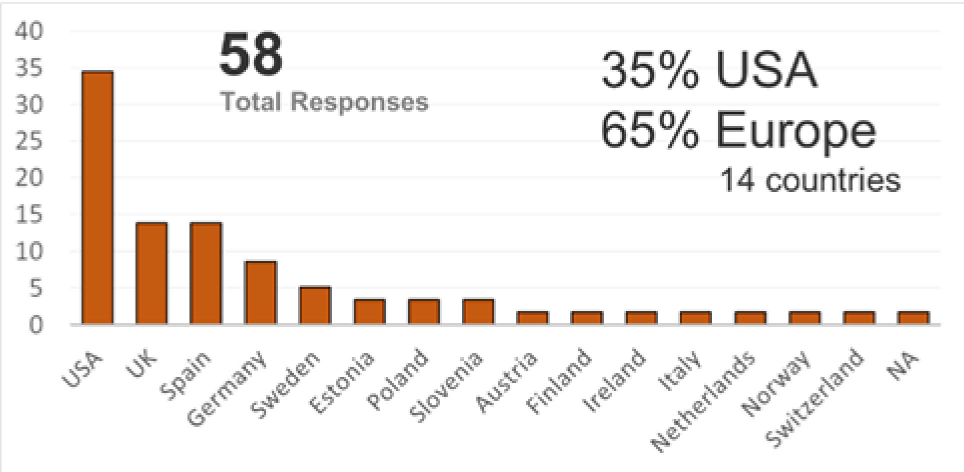

Figure 6. Distribution of responses by country.

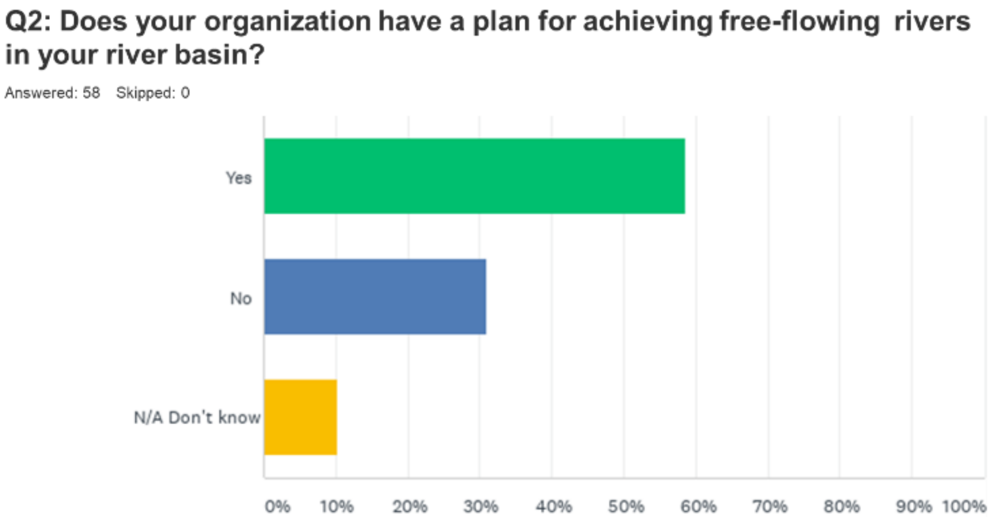

Figure 7. Responses to Q2 in relation to planning for free-flowing rivers.

Most organizations consulted (~60%) had a plan to achieve free-flowing river status in their basins (**Figure 7**) and most (34%) used expert judgment, consultation with stakeholders (17%) and a combination of methods (28%) to prioritize barriers. Only 12% used dedicated software or algorithm (**Figure 8**).

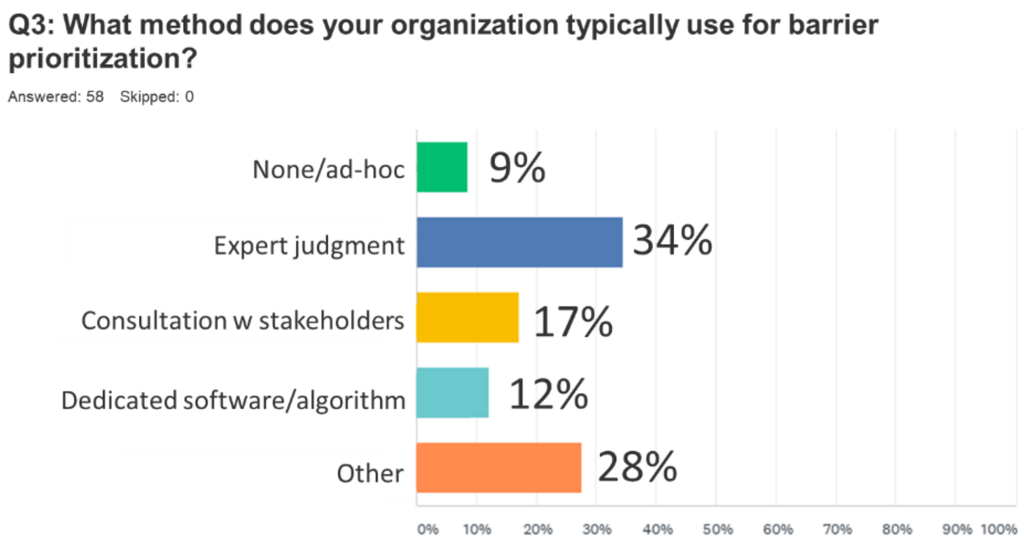

Figure 8. Responses to Q3 in relation to methods used for barrier prioritization.

The barrier attributes most frequently used by practitioners in barrier prioritization were the barrier ownership and rights, the results of field surveys, and the obsolescence and conservation status of barriers. In contrast, flow data and the biodiversity value of a catchment were considered less frequently (**Figure 9**).

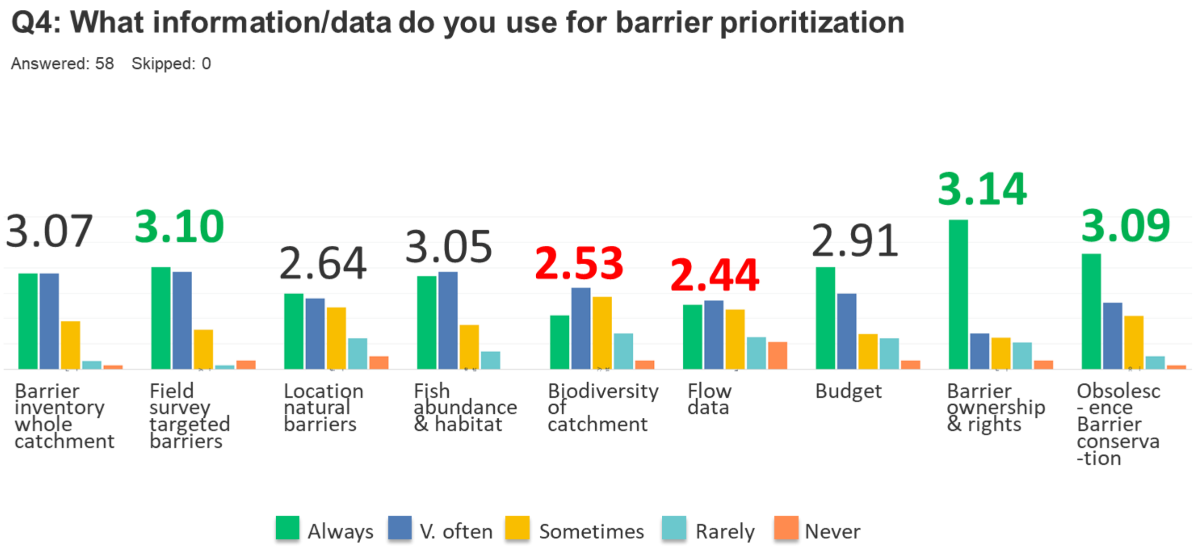

Figure 9. Responses to Q4 in relation to information used for barrier prioritization. The numbers above each answer indicate the support for each metric on a five-point Likert scale (0-4), with the highest inferred support being written in green and the lowest support in red.

The most important rational flagged by practitioners to prioritize barriers was to improve fish passage, with cost being the least important one (**Figure 10**).

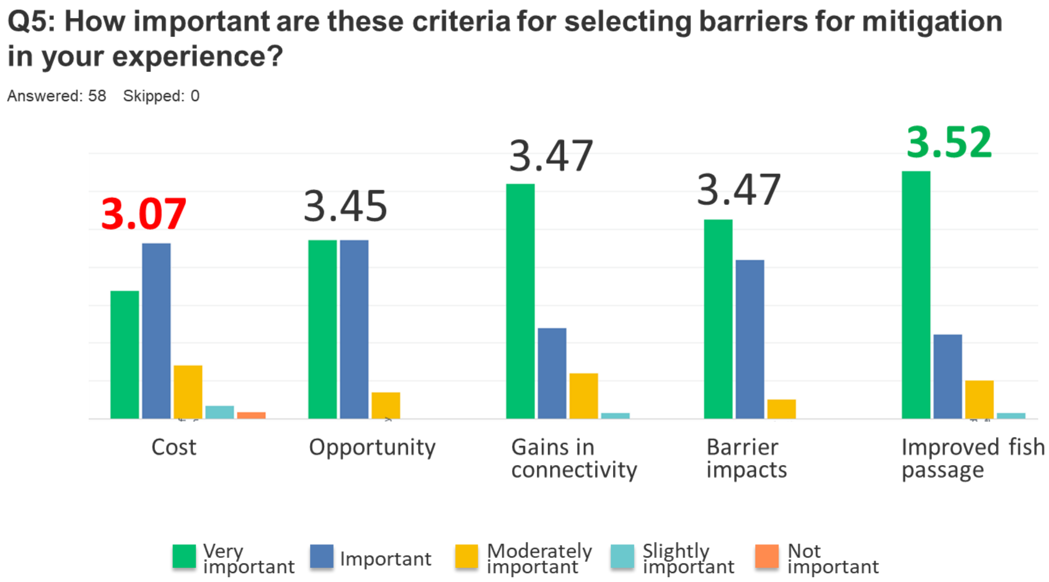

Figure 10. Responses to Q5 in relation to criteria used for barrier prioritization. The numbers above each answer indicate the support for each criteria on a five-point Likert scale (0-4), with the highest inferred support being written in green and the lowest support in red.

In terms of desirable features of barrier prioritization software, practitioners highlighted the flexibility to evaluate different scenarios and the ability to link with existing GIS databases as the most important. Open source software and explicit consideration of uncertainty were the least important (**Figure 11**).

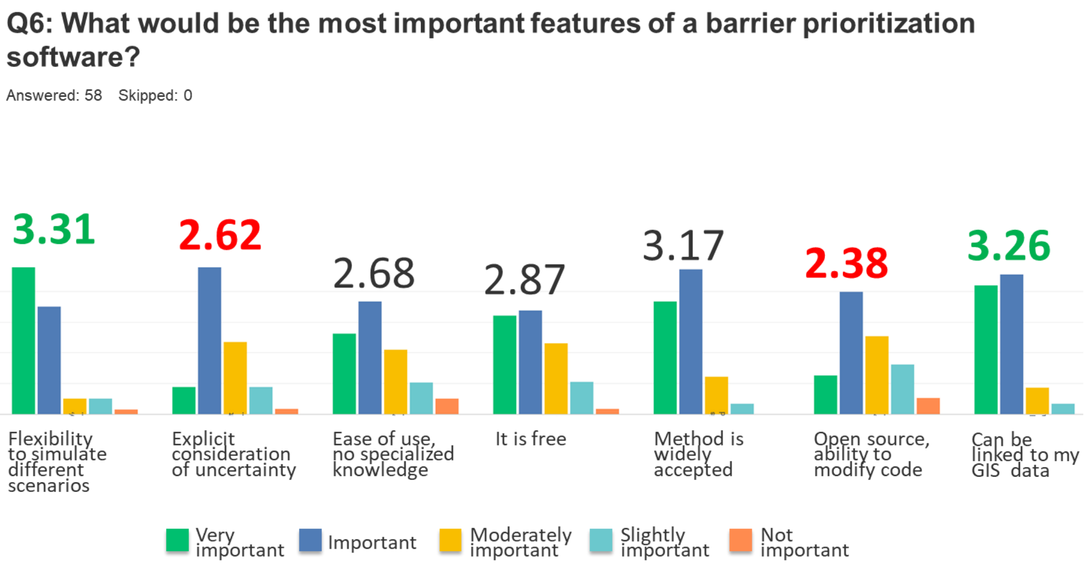

Figure 11. Responses to Q6 in relation to desirable features of barrier prioritization software. The numbers above each answer indicate the support for each criteria on a five-point Likert scale (0-4), with the highest inferred support being written in green and the lowest support in red.

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