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Review

Operational methods for prioritizing the removal of river barriers: Synthesis and guidance

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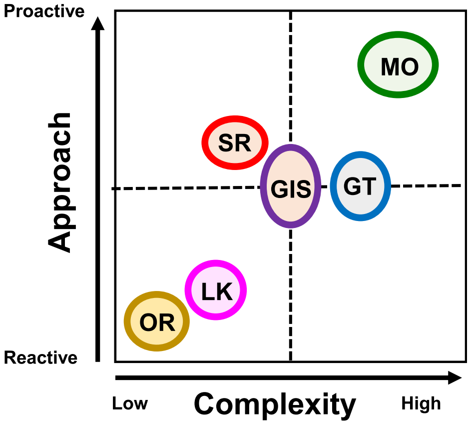
HIGHLIGHTS

- River fragmentation depends on the number and location of barriers, not on barrier size.
- Barrier removal costs increase with barrier height.
- A small proportion of barriers typically causes most of the fragmentation.
- Acting on many small barriers is more efficient than acting on fewer larger dams.
- Consideration of opportunities, costs, and gains can help locate low hanging fruit (easiest targets) in barrier removal.

GRAPHICAL ABSTRACT



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ABSTRACT

Barrier removal can be an efficient method to restore river continuity but resources available for defragmenting rivers are limited and a prioritization strategy is needed. We review methods for prioritizing barriers for removal and report on a survey asking practitioners which barrier prioritization methods they use. Opportunities for barrier removal depend to a large extent on barrier typology, as this dictates where barriers are normally located, their size, age, condition, and likely impacts. Crucially, river fragmentation depends chiefly on the number and location of barriers, not on barrier size, while the costs of barrier removal typically increase with barrier height. Acting on many small barriers will often be more cost-efficient than acting on fewer larger structures. Barriers are not randomly distributed and a small proportion of barriers have a disproportionately high impact on fragmentation, therefore targeting these ‘fragmentizers’ can result in substantial gains in connectivity. Barrier prioritization methods can be grouped into six main types depending on whether they are reactive or proactive, whether they are applied at local or larger spatial scales, and whether they employ an informal or a formal approach. While mathematical optimization sets the gold standard for barrier prioritization, a hybrid approach that explicitly considers uncertainties and opportunities is likely to be the most effective. The effectiveness of barrier removal can be compromised by inaccurate stream networks, erroneous barrier coordinates, and underestimation of barrier numbers. Such uncertainties can be overcome by ground truthing via river walkovers and predictive modelling, but the cost of collecting additional information must be weighed against the cost of inaction. To increase the success of barrier removal projects, we recommend that barriers considered for removal fulfill four conditions: (1) their removal will bring about a meaningful gain in connectivity;

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(2) they are cost-effective to remove; (3) they will not cause significant or lasting environmental damage, and (4) they are obsolete structures. Mapping barrier removal projects according to the three axes of opportunities, costs, and gains can help locate any ‘low hanging fruit.’

Contents

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). Barriers as small as 20 cm in height can impair the movement of weak fish swimmers (Jones et al., 2021a) and low head barriers can negatively impact macrophyte dispersal (Jones et al., 2020b). Therefore, although minimum height thresholds have often been used to identify barriers to fish movement (typically >50 cm), there is not really a minimum barrier height that will avoid river 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.’ By barrier removal we mean here the restoration of continuity by the removal of infrastructure that cause longitudinal discontinuity, but also the elimination of barrier effects that such infrastructure may cause on river fragmentation. The barriers that one may wish to prioritize for removal include not just those that affect fish movements, but also other river processes. In what follows, we focus on longitudinal (i.e., transversal) artificial instream barriers. We exclude lateral and vertical barriers, such as embankments, levees, or channelizations, not because these are unimportant, but simply because these are typically absent from most barrier inventories.

2. Barrier typology and why it matters

The majority of longitudinal instream barriers can be classified into six main types, as suggested by Belletti et al. (2020), based on key features and the extent of habitat modification (Jones et al., 2020a) (Fig. 1). Dams and weirs may be the most recognizable instream barriers, but they are not the only ones. Many other human activities, such as water abstraction, flood control, navigation, or crossing waterways, break longitudinal river continuity and impact on riverine habitats and fluvial ecosystems (Carpenter et al., 2011; Grizzetti et al., 2017).

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 (Fig. 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 (Perera et al., 2021), which will favour 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 (World Commission on Dams, 2000), 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, such barriers 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 (Fig. 2).

3. Why prioritize?

A common underlying goal of many barrier mitigation programs is to maximize the length of reconnected habitats given some available resources. However, resources available for barrier mitigation are seldom enough, so some sort of prioritization process is required to mitigate barrier effects, which may include barrier removal, but also barrier repair, replacement, and retrofitting. All instream barriers cause some impacts, but because barriers are not evenly distributed within a catchment and their impacts differ (Fig. 2), the removal of some barriers will be more beneficial than the removal of others. Indeed, the removal of some barriers may not

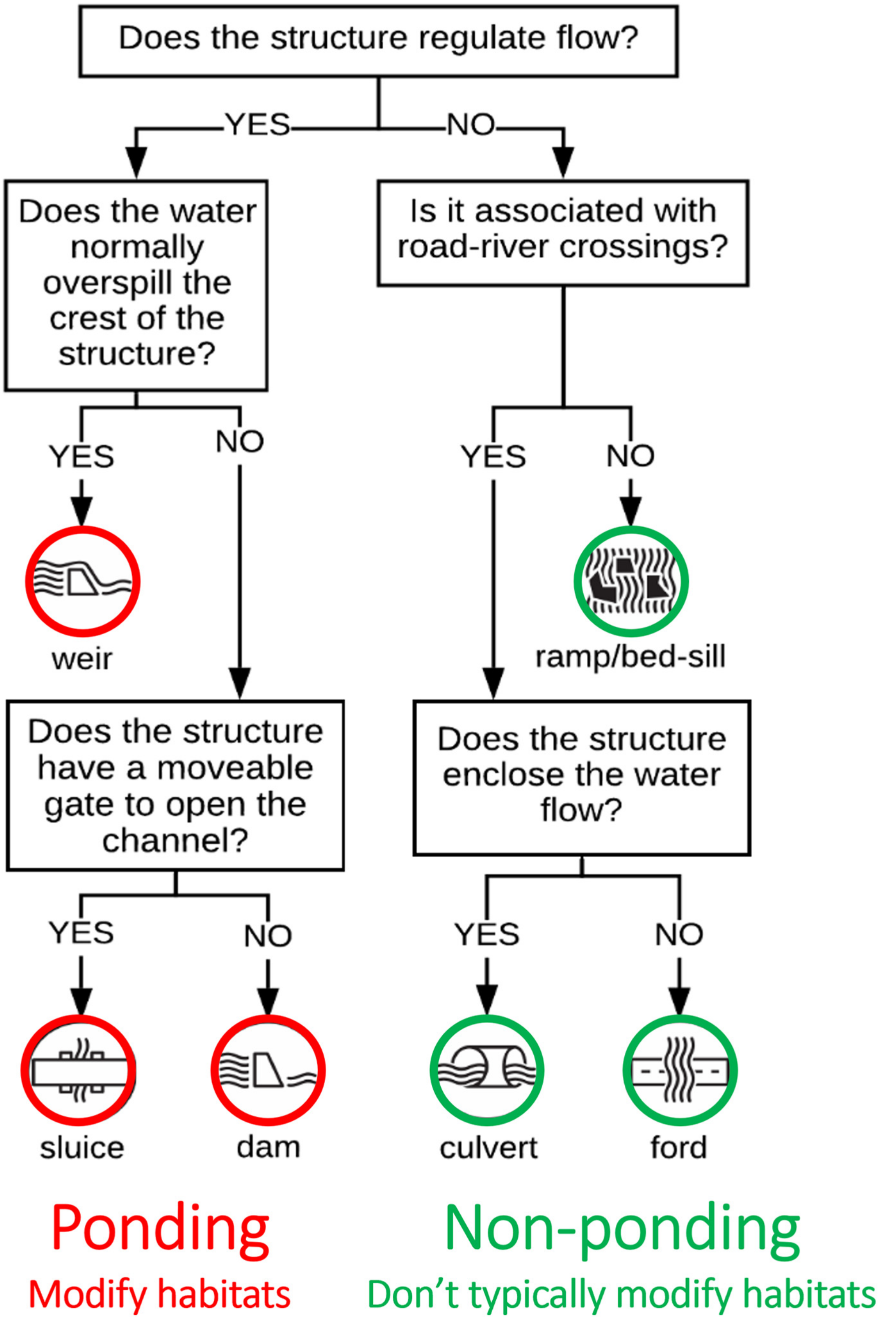


Fig. 1. Classification of six main barrier types (adapted from Jones et al., 2020a).

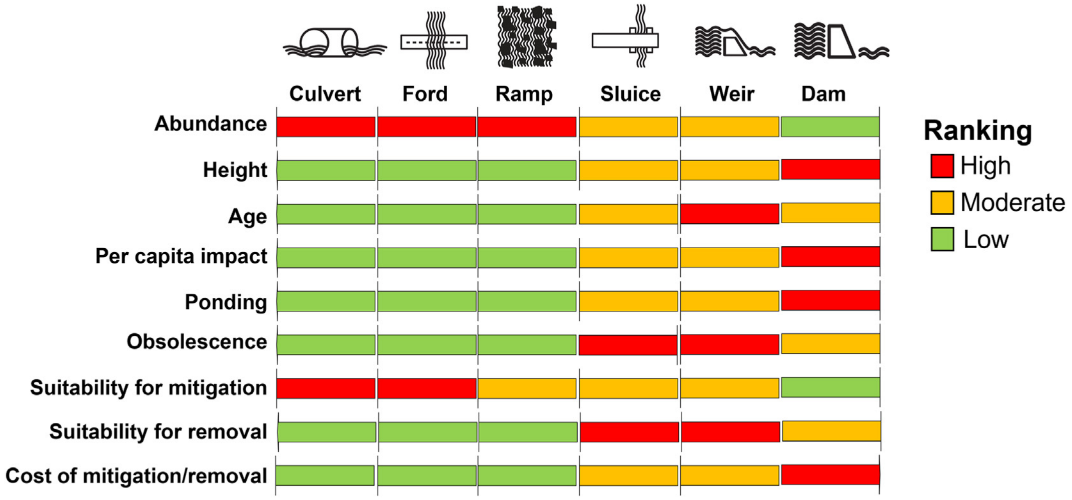
be beneficial at all if, for example, they allow the spread of aquatic invasive species, mobilize toxic sediments or help reconnect polluted waters, thus damaging good habitats with poor ones (Bednarek, 2001; Milt et al., 2018; Stanley and Doyle, 2003; Tullos et al., 2016). There is, therefore, a need to prioritize barriers whose removal should normally fulfill three conditions:

1. Their removal will bring about a meaningful gain in connectivity;
2. They can be removed in a cost-efficient way;
3. They will not cause significant or lasting environmental damage.

Given that most barriers still serve a purpose - they were built to control and divert the flow of water, to stabilize river beds or to accommodate road crossings (Belletti et al., 2020), one should ideally also target barriers that fulfill a fourth condition, namely (4) they are obsolete structures that are no longer in use.

3.1. Death by a thousand cuts from small barriers & implications for barrier removal

The impact of barriers on river fragmentation depends chiefly on their number and location (Cote et al., 2009), not their height. Hence, the cumulative impact of many small barriers is usually much greater than that caused by a few, larger structures (Athayde et al., 2019; Consuegra et al., 2021; Wagner et al., 2019). Here, the adage of 'death by a thousand cuts' cannot be more apt. For example, 68 % of barriers in Europe are <2 m in height and a mere 0.1 % are large (>15 m) dams (Belletti et al., 2020). Moreover, while small dams are numerous, they only make a small contribution to energy production (Morden et al., 2022; Seliger et al., 2016). In Romania, for example, small dams represent 86 % of hydropower plants but contribute only 3 % to hydropower production (Costea et al., 2021). Given that barrier removal costs typically increase with barrier height (Heinz Center, 2002; Neeson et al., 2018), acting on many small barriers



	Culvert	Ford	Ramp	Sluice	Weir	Dam
Abundance	🟥	🟥	🟥	🟨	🟨	🟩
Height	🟩	🟩	🟩	🟨	🟨	🟥
Age	🟩	🟩	🟩	🟨	🟥	🟨
Per capita impact	🟩	🟩	🟩	🟨	🟨	🟥
Ponding	🟩	🟩	🟩	🟨	🟨	🟥
Obsolescence	🟩	🟩	🟩	🟥	🟥	🟨
Suitability for mitigation	🟥	🟥	🟨	🟨	🟨	🟩
Suitability for removal	🟩	🟩	🟩	🟥	🟥	🟨
Cost of mitigation/removal	🟩	🟩	🟩	🟨	🟨	🟥

Ranking

🟥 High
🟨 Moderate
🟩 Low

Fig. 2. Characteristics of different barrier types and how these can affect decisions about barrier removal. The colour represents the ranking of each trait (note these are merely indicative).

may be more cost-efficient (in terms of connectivity gains) and less confrontational than acting on fewer larger structures.

4. What to prioritize?

A common goal of prioritization methods is to increase the distribution and abundance of one or more target species, typically fish (Branco et al., 2014; Ioannidou and O'Hanley, 2019; Kuby et al., 2005; O'Hanley, 2011; Segurado et al., 2013). While this can help address the needs of particular species, priorities may change depending on the target species and or wider conservation aims. For example, the benefits of reconnecting a river reach may differ substantially if the target is a highly mobile versus a more sedentary species, but may be the same for improving sediment transport or restoring 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, one could seek to maximize the size of the largest single reach unimpeded by artificial barriers (O'Hanley, 2011) or the total barrier-free length (Jones et al., 2019). Similarly, one could also take into account not just the size of the reconnected habitats, but also their quality (Diebel et al., 2015; Rodeles et al., 2019). Connecting good quality habitats is important to avoid the risk of stranding posed by 'ecological traps', sensu (Robertson and Hutto, 2006), caused by pollution, artificial flows, or extreme water temperatures (Palmer and Ruhi, 2019; Seliger and Zeiringer, 2018). In this context, predicted changes in water quality resulting from barrier removal can be incorporated into the barrier prioritization process (Guetz, 2020).

5. How to prioritize?

5.1. Overview of barrier prioritization methods

There are dozens of different barrier prioritization methods, which typically consider not just barrier removal but also other mitigation options, such as repair, retrofitting and various forms of technical easement, most commonly in relation to fish passage. These are reviewed by Kemp and O'Hanley (2010), King and 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 broadly classified into six main families (Table 1; Fig. 3), depending on the extent to which they are more reactive (i.e. reacting to opportunities) or proactive (i.e. forward planning), the spatial scales they are typically applied at, and their degree of complexity (McKay et al., 2020; Weiter, 2014). These include opportunistic response

Table 1

Characteristics of the six main types of barrier prioritization methods (OR = Opportunistic response; LK = Local Knowledge; SR = Score & Rank; GIS = Geographic Information System; GT = Graph Theory; MO = Mathematical Optimization) benchmarked by trait (L = Low; M = moderate; H = High).

	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) Martin and Apse (2011)	Cote et al. (2009) Segurado et al. (2013)	O'Hanley and Tomberlin (2005) Kuby et al. (2005)

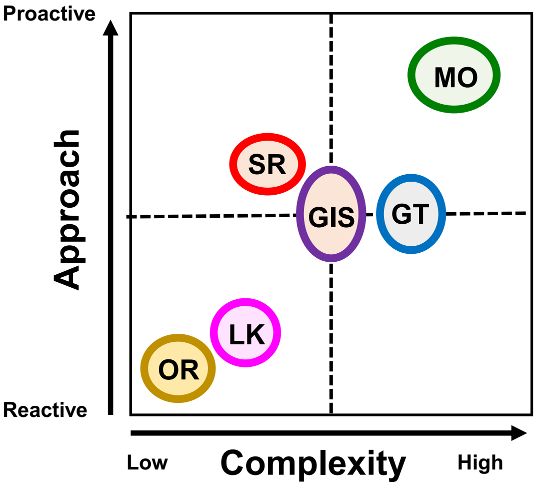


Fig. 3. Classification of the six main barrier prioritization methods according to their complexity and type of approach. OR - opportunistic response; LK - local knowledge & expert opinion; SR - scoring and ranking; GIS - GIS scenario analysis; GT – graph theory; MO - mathematical optimization.

(OR), local knowledge and expert opinion (LK), scoring and ranking (SR), geographic information system (GIS) scenario analysis, graph theory (GT), and mathematical optimization (MO).

These six prioritization methods can be subdivided into two main classes: 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 opinion. 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.

5.1.1. Informal methods

5.1.1.1. 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 (Lowry, 2003; Pohl, 2002; Ryan Bellmore et al., 2017). 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 and eel, will benefit largely depends on where a dam is located relative to other barriers. Removing a dam above

Table 2
Cross comparison of informal and formal barrier prioritization methods, adapted and expanded 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 rigour, 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

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 (O'Hanley, 2011).

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 (Jones et al., 2019), 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.

5.1.1.2. Local knowledge & expert opinion. Use of local knowledge about barriers together with input of experts from various fields of domain (e.g., biology, hydrology, engineering, transportation) is far and away the most widely used of any barrier prioritization method. Here, the aim is usually 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 can help identify 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 too difficult since local experts from each catchment need to be involved. Even when the problem is broken down by catchments, it becomes difficult to compare priorities across catchments and, in turn, allocate funding. A good example of the difficulty of employing expert judgment comes from Europe. Many of the national agencies with statutory responsibility for maintaining free passage for migratory fish lack any coherent approach to barrier prioritization (Schäfer, 2021). Often, they rely on a strategy in which regional authorities or local rivers trusts are tasked with coming up with a list of high priority barriers in their respective region or catchment. The manner in which priorities are arrived at is left to their discretion without any common set of criteria. To compound the problem, species of interest across different regions/catchments are not always the same. National level priorities, when there are any, are ultimately derived by 'filtering' various regional priorities using some ad-hoc process which is not repeatable or transparent, highlighting the weakness of using expert judgment alone when working at supra-basin scales.

5.1.2. Formal methods

5.1.2.1. Scoring & ranking. Scoring and ranking is the most popular type of formal method used for prioritizing barrier mitigation decisions (Hoenke et al., 2014; Kocovsky et al., 2009; Martin, 2019a; Nunn and Cowx, 2012; Taylor and Love, 2003; WDFW, 2009). Here, 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 (Hoenke et al., 2014; Martin, 2019a; Nunn and 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 and 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, especially in the case of diadromous fish, can result in proposals to mitigate barriers located above impassable downstream barriers even though this would produce no habitat gain at all.

While more elaborate scoring systems are able to take into account barrier spatial structure (e.g., number of downstream barriers), scoring and ranking suffers from an even more fundamental shortcoming, which is that decisions about individual barriers 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 given barrier is not fixed, but depends on whether other barriers downstream and upstream have or will be mitigated as well. For this reason, scoring and ranking typically fails to find good quality solutions (especially at low budgets), as it cannot deal with multiple barriers simultaneously. 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.

5.1.2.2. 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 simple connectivity metrics like total reconnected stream distance in the upstream and or downstream directions (Barrios, 2011; Martin, 2019a; Martin, 2019b; Martin and Apse, 2011; Martin et al., 2014). This information can subsequently be used to produce a ranked list (often involving some sort of scoring and ranking procedure) of single barrier interventions or compare different portfolios of barriers (one online tool is available here: https://maps.freshwaternetwork.org/northeast/).

This method is visually appealing, easy to communicate and can be very effective in conveying gains under various *what-if* scenarios (e.g., primary restoration focus and budget). 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. Stakeholder involvement and uptake may also be low if the implementation is not user-friendly or easily accessible online. Importantly, the choice of attributes to use or consider can be very subjective, which hampers repeatability and transparency. As with previous prioritization methods, there is no way of knowing whether a particular barrier mitigation solution is cost-efficient.

5.1.2.3. 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 approaches (Erős et al., 2011; Segurado et al., 2013) are 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 completely passable or completely impassable. This makes these indices rather 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 (i.e., one that considers the spatial relationship of all barriers in the catchment, rather than each barrier in isolation). 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 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.

5.1.2.4. Mathematical optimization. The final and most sophisticated barrier prioritization method is mathematical optimization, developed mostly over the last two decades (King and 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 and 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). This ensures the best possible use of limited resources. The use of optimization has other advantages as well (Kemp and O'Hanley, 2010), including greater transparency and repeatability, increased flexibility, and explicit consideration of uncertainty. For example, the fact that optimization methods rely on clear and objective criteria makes them more transparent and repeatable than other methods. 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 and 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, 2017).

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 and 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 modelling and fine-tuning later on.

Optimization, however, is not without drawbacks. It can be viewed as excessively prescriptive (McKay et al., 2020) and tends to ignore local knowledge (Fox et al., 2016), which may antagonize some stakeholders (Sneddon et al., 2017) and make communication of results difficult. It also requires 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 systems, such as OptiPass (O'Hanley, 2014) and the River Infrastructure Planning (RIP) tool (O'Hanley et al., 2020) should facilitate more mainstreaming use of optimization in barrier removal programs. Other downsides include the fact that (1) 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) the quality of solutions tends to be heavily reliant on the availability of complete and accurate barrier location data; and (3) 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 may 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. Indeed, studies have found that a single large budget may be more efficient than 'toping-up' annual budgets totaling the same amount so that expensive, but high impact removals can be actioned (Neeson et al., 2015). In some cases, however, solutions are often nested - at least within certain budgets. For this reason, it is important to run optimization models across multiple budgets to ascertain the degree of nestedness and where any budget thresholds may occur, as well as when diminishing returns from barrier removal begin to set in.

To address the risk of some targeted barriers becoming in effect "non-removable," rigorous sensitivity analysis is recommended. Here, different "what-if" barrier exclusion scenarios can be run to assess how robust an optimized solution really is. Further research on this topic is warranted to better mitigate such a risk.

Taken together, optimization sets the gold standard for efficient barrier mitigation planning. To be practical, however, it needs to factor in the constraints imposed by uncertainties and opportunities. A hybrid system, therefore, is probably best on the grounds of effectiveness and robustness.

5.2. Barrier prioritization in practice

An online questionnaire consisting of 6 questions was developed with *SurveyMonkey* and sent to ~200 river restoration practitioners across

Europe and North America (drawn from our network and a list of registered attendees to a river connectivity webinar). A total of 58 responses were received from 15 countries one month later in July 2021 (Fig. S1), representing a ~29 % response rate.

Most organizations consulted (~60 %) had a plan to achieve free-flowing river status in their basins (Fig. S2) and most (34 %) used expert judgment, consultation with stakeholders (17 %), or a combination of methods (28 %) to prioritize barriers for mitigation. Only 12 % used dedicated software or a specific algorithm (Fig. S3).

The barrier attributes most frequently used by practitioners in barrier prioritization were 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 (Fig. S4). The most important rational flagged by practitioners to prioritize barriers was to improve fish passage, with cost being the least important one (Fig. S5). In terms of desirable features of a barrier prioritization software, practitioners highlighted the flexibility to evaluate different scenarios and the ability to link with existing GIS databases as the most important ones. Open source software and explicit consideration of uncertainty were deemed to be least important (Fig. S6).

6. Prioritizing the smart way – operational considerations and recommendations

6.1. Prioritizing barrier removal versus prioritizing barrier mitigation

A 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 Open Rivers Programme (ORP) 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 Fig. 2, most non-flow regulating barriers cannot easily be removed, they can only be modified or replaced by something else, like a bridge in the case of a culvert, which will incur additional costs and may rule them out from funding for barrier removal schemes.

6.2. Identifying the 'fragmentizers'

River walkover surveys indicate that barriers are not distributed at random, they tend to be clustered (Atkinson et al., 2020; Jones et al., 2019; Sun et al., 2020). This has two important consequences. First, it means that barrier impacts on stream fragmentation are less severe than would have been the case if barriers had been distributed regularly or randomly (Diebel et al., 2015). It also means that a relatively small proportion of barriers (call them 'fragmentizers') will likely have an disproportionate large impact on fragmentation. These 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 (Fig. 4). For example, in the Willamette River, USA, removing just 8 % of barriers would reconnect 52 % of the basin (Kuby et al., 2005). Several studies have shown that the removal of certain 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).

6.3. Locating the low-hanging fruit and capitalizing on opportunities

Most barriers cannot be easily removed, only mitigated. This means that opportunities need to be factored into the barrier prioritization process, particularly if removal is not an option. Perhaps surprisingly, 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. Barrier removal projects can be mapped into three axes – opportunity, cost and gains – and this can help locate any 'low hanging fruit' (Fig. 5). Just as gains change depending on the interactive effects of multiple barriers, so do opportunities. Opportunities will develop over time as infrastructure age and require repair, replacement or decommissioning (Neeson et al., 2018), but also as support for barrier removal grows (WWF, 2021). A snowballing effect might be expected at the catchment scale because acting on some initial barriers will likely open opportunities for acting on others.

6.4. 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 have been 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 current passability of structures by different species and would be passability increases 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 (Cid et al., 2022; Zaidel et al., 2021; Zhao et al., 2021). 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 (Mulligan et al., 2021), because for every barrier recorded there may be another one missing (Belletti et al., 2020; Jones et al., 2019; Sun et al., 2020). Unrecorded barriers diminish the effectiveness of dam removal, while the possibility that it may not be practically or logistically feasible (now or in the future) to remove certain barriers limits connectivity gains and requires a revision of priorities. In practical terms, two ways that can be used to fill data gaps and reduce uncertainties caused by incomplete barrier records are 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 or other predictive models (Belletti et al., 2020; Buchanan et al., 2022; Januchowski-Hartley et al., 2021; Januchowski-Hartley et al., 2019; Jones et al., 2020a).

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

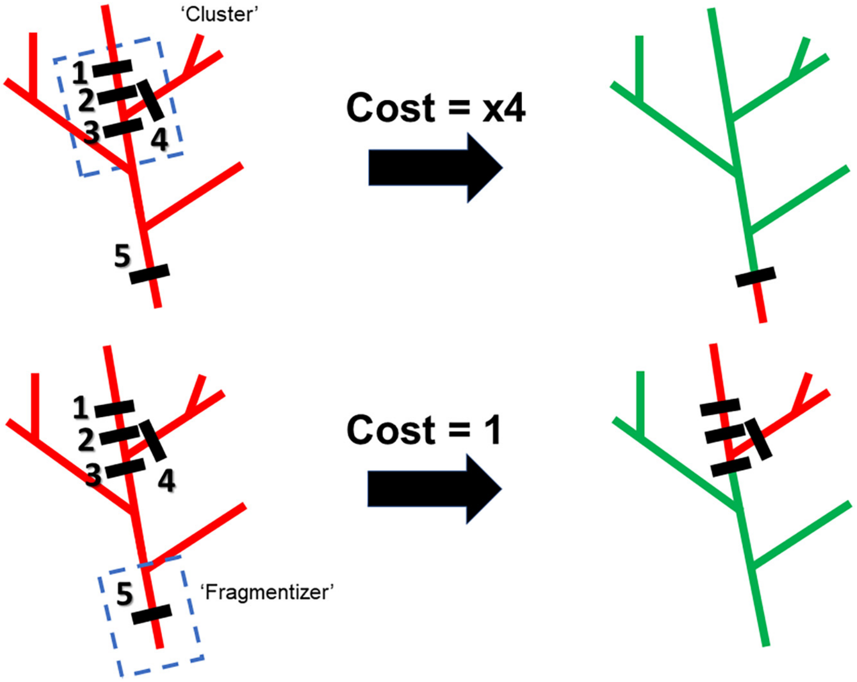


Fig. 4. Stream barriers are not randomly distributed, they tend to be found in clusters (barriers 1–4). Acting on clusters will not normally yield significant gains, unless all barriers in a cluster are mitigated or removed (top). However, acting on some isolated barriers such as barrier 5 (a 'fragmentizer', 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.

underestimate stream length by a factor of 3 because first and second order streams are poorly mapped (Kristensen and 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 (Cooper et al., 2021; Hermoso et al., 2021; Jones et al., 2021b; Muha et al., 2021) and with future demands for water resources (Baumgartner et al., 2021; Duarte et al., 2021; Radinger and García-Berthou, 2020; Tickner et al., 2020). Many would argue that the answer to resolving issues around uncertainty is to 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.

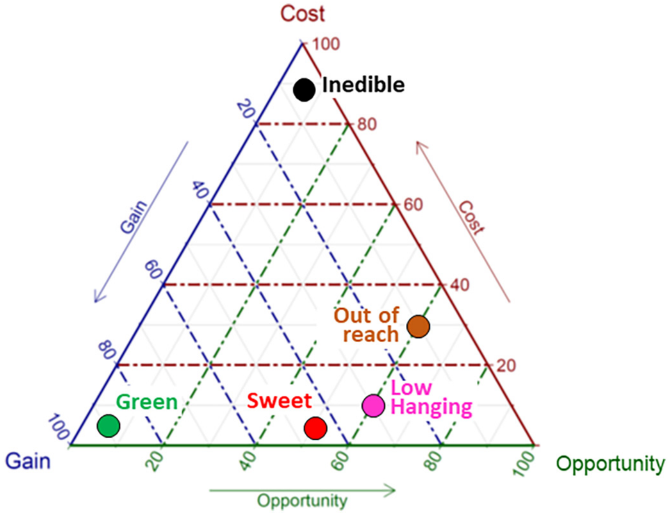


Fig. 5. Mapping of barrier removal projects according to opportunities, cost and gains can help locate the 'low hanging fruit'. Projects that produce limited gains are regarded as 'inedible', regardless of what the opportunity or costs might be. Projects that can achieve high connectivity gains at low 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'.

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.

Adaptive planning (Cid et al., 2022), 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. But no matter what prioritization approach is ultimately adopted, decision makers need to be mindful that barrier priorities should not be set in stone. Change and the unexpected, both bad and good, are sometimes forced upon even the most carefully laid plans. Planning, therefore, needs to be ever agile and flexible enough to adapt.

6.5. Accounting for 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 (Birnie-Gauvin et al., 2017; Duarte et al., 2021). 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 and Cragg-Hine, 2003) and are much lower for weaker swimmers (Legalle et al., 2005).

6.6. Future-proofing barrier removal and the do-nothing option

All barriers have a finite life span and proper maintenance is essential but also costly (Neeson et al., 2015). Opportunities presented by barrier obsolescence must be weighed against 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 (Zhao et al., 2021). In Europe, barrier impacts are expected to worsen in countries where climate will get drier and flows are expected to decrease (e.g., the Mediterranean region) but will lessen in places expected to become wetter (e.g., Scandinavia (Duarte et al., 2021)).

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CRediT authorship contribution statement

Garcia de Leaniz: Conceptualization, Writing- Original draft preparation. Visualization.

O'Hanley: Writing- Reviewing and Editing, Visualization, Software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Garcia de Leaniz reports financial support was provided by The Nature Conservancy.

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