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

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1 **Abstract**

2 Barrier removal can be an efficient method to restore river continuity but resources

3 available for defragmenting rivers are limited and a prioritization strategy is needed.

4 We review methods for prioritizing barriers for removal and report on a survey asking

5 practitioners which barrier prioritization methods they use. Opportunities for barrier

6 removal depend to a large extent on barrier typology, as this dictates where barriers

7 are normally located, their size, age, condition, and likely impacts. Crucially, river

8 fragmentation depends chiefly on the number and location of barriers, not on barrier

9 size, while the costs of barrier removal typically increase with barrier height. Acting

10 on many small barriers will often be more cost-efficient than acting on fewer larger

11 structures. Barriers are not randomly distributed and a small proportion of barriers

12 have a disproportionately high impact on fragmentation, therefore targeting these

13 'fragmentizers' can result in substantial gains in connectivity. Barrier prioritization

14 methods can be grouped into six main types depending on whether they are reactive

15 or proactive, whether they are applied at local or larger spatial scales, and whether

16 they employ an informal or a formal approach. While mathematical optimization sets

17 the gold standard for barrier prioritization, a hybrid approach that explicitly considers

18 uncertainties and opportunities is likely to be the most effective. The effectiveness of

19 barrier removal can be compromised by inaccurate stream networks, erroneous

20 barrier coordinates, and underestimation of barrier numbers. Such uncertainties can

21 be overcome by ground truthing via river walkovers and predictive modelling, but the

22 cost of collecting additional information must be weighed against the cost of inaction.

23 To increase the success of barrier removal projects, we recommend that barriers

24 considered for removal fulfill four conditions: (1) their removal will bring about a

25 meaningful gain in connectivity; (2) they are cost-effective to remove; (3) they will not

26   cause significant or lasting environmental damage, and (4) they are obsolete

27   structures. Mapping barrier removal projects according to the three axes of

28   opportunities, costs, and gains can help locate any 'low hanging fruit.'

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) (Figure 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 (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 (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

77 the only option. Clearly, to remove barriers sensibly, one needs to know how they differ

78 and why they were built in the first place (Figure 2).

79

80 **3. Why prioritize?**

81 A common underlying goal of many barrier mitigation programs is to maximize the

82 length of reconnected habitats given some available resources. However, resources

83 available for barrier mitigation are seldom enough, so some sort of prioritization

84 process is required to mitigate barrier effects, which may include barrier removal, but

85 also barrier repair, replacement, and retrofitting. All instream barriers cause some

86 impacts, but because barriers are not evenly distributed within a catchment and their

87 impacts differ (Figure 2), the removal of some barriers will be more beneficial than the

88 removal of others. Indeed, the removal of some barriers may not be beneficial at all if,

89 for example, they allow the spread of aquatic invasive species, mobilize toxic

90 sediments or help reconnect polluted waters, thus damaging good habitats with poor

91 ones (Bednarek, 2001; Milt et al., 2018; Stanley and Doyle, 2003; Tullos et al., 2016).

92 There is, therefore, a need to prioritize barriers whose removal should normally fulfill

93 three conditions:

94

95   1. Their removal will bring about a meaningful gain in connectivity;

96   2. They can be removed in a cost-efficient way;

97   3. They will not cause significant or lasting environmental damage.

98

99 Given that most barriers still serve a purpose - they were built to control and divert the

100 flow of water, to stabilize river beds or to accommodate road crossings (Belletti et al.,

6

101 2020), one should ideally also target barriers that fulfill a fourth condition, namely (4)

102 they are obsolete structures that are no longer in use.

103

104 **Death by a thousand cuts from small barriers & implications for barrier removal**

105 The impact of barriers on river fragmentation depends chiefly on their number and

106 location (Cote et al., 2009), not their height. Hence, the cumulative impact of many

107 small barriers is usually much greater than that caused by a few, larger structures

108 (Athayde et al., 2019; Consuegra et al., 2021; Wagner et al., 2019). Here, the adage

109 of 'death by a thousand cuts' cannot be more apt. For example, 68% of barriers in

110 Europe are less than 2 m in height and a mere 0.1% are large (>15 m) dams (Belletti

111 et al., 2020). Moreover, while small dams are numerous, they only make a small

112 contribution to energy production (Morden et al., 2022; Seliger et al., 2016). In

113 Romania, for example, small dams represent 86% of hydropower plants but contribute

114 only 3% to hydropower production (Costea et al., 2021). Given that barrier removal

115 costs typically increase with barrier height (Heinz Center, 2002; Neeson et al., 2018),

116 acting on many small barriers may be more cost-efficient (in terms of connectivity

117 gains) and less confrontational than acting on fewer larger structures.

118

119 **4. What to prioritize?**

120 A common goal of prioritization methods is to increase the distribution and abundance

121 of one or more target species, typically fish (Branco et al., 2014; Ioannidou and

122 O'Hanley, 2019; Kuby et al., 2005; O'Hanley, 2011; Segurado et al., 2013). While this

123 can help address the needs of particular species, priorities may change depending on

124 the target species and or wider conservation aims. For example, the benefits of

125 reconnecting a river reach may differ substantially if the target is a highly mobile versus

126 a more sedentary species, but may be the same for improving sediment transport or

127 restoring whole river processes. An alternative to taxa-driven targets is to reconnect

128 good quality habitats, as opposed to extending the range of specific target species

129 (Diebel et al., 2015). For example, one could seek to maximize the size of the largest

130 single reach unimpeded by artificial barriers (O'Hanley, 2011) or the total barrier-free

131 length (Jones et al., 2019). Similarly, one could also take into account not just the size

132 of the reconnected habitats, but also their quality (Diebel et al., 2015; Rodeles et al.,

133 2019). Connecting good quality habitats is important to avoid the risk of stranding

134 posed by 'ecological traps', *sensu* (Robertson and Hutto, 2006), caused by pollution,

135 artificial flows, or extreme water temperatures (Palmer and Ruhi, 2019; Seliger and

136 Zeiringer, 2018). In this context, predicted changes in water quality resulting from

137 barrier removal can be incorporated into the barrier prioritization process (Guetz,

138 2020).

139

140 **5. How to prioritize?**

141 **5.1 Overview of barrier prioritization methods**

142 There are dozens of different barrier prioritization methods, which typically consider

143 not just barrier removal but also other mitigation options, such as repair, retrofitting

144 and various forms of technical easement, most commonly in relation to fish passage.

145 These are reviewed by (Kemp and O'Hanley, 2010; King and O'Hanley, 2016; McKay

146 et al., 2017; McKay et al., 2020; Moody et al., 2017), among others. In addition, there

147 are at least 23 metrics of river fragmentation and 13 metrics of flow alteration that one

148 could use to assess baseline conditions and predict the response of barrier removal

149 (Jumani et al., 2020), so choosing a barrier removal prioritization method can be a

150 daunting task (King et al., 2021). Barrier prioritization methods can be broadly

151   classified into six main families (Table 1; Figure 3), depending on the extent to which

152   they are more reactive (i.e. reacting to opportunities) or proactive (i.e. forward

153   planning), the spatial scales they are typically applied at, and their degree of

154   complexity (McKay et al., 2020; Weiter, 2014). These include opportunistic response

155   (OR), local knowledge and expert opinion (LK), scoring and ranking (SR), geographic

156   information system (GIS) scenario analysis, graph theory (GT), and mathematical

157   optimization (MO).

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

159   informal and formal (Table 2). Informal methods are the most widely used approach,

160   particularly outside North America. They are distinguished by their qualitative nature

161   and include both opportunistic response and expert opinion. Formal methods, in

162   contrast, employ some sort of structured, quantitative analysis in which each criterion

163   for prioritizing barriers must be explicitly defined and measured. Each approach has

164   strengths and weaknesses and no method is best under all conditions (McKay et al.,

165   2020). These are briefly discussed below.

166

167   **5.1.1 Informal methods**

168   *Opportunistic response*

169 Opportunistic response, also called reactive response (McKay et al., 2020), relies on

170 a very simple strategy of mitigating barriers as and when opportunities arise, often in

171 response to barrier owners seeking to remove older, legacy structures. Opportunistic

172 response is a mostly passive strategy that has the benefit of requiring little or no

173 strategic forward planning, thus eliminating analytical challenges and potentially

174 facilitating the removal of more barriers than would otherwise be feasible due to lower

175 logistical hurdles. American Rivers, for example, has removed dozens of dams in the

176   US by identifying and working with owners of aging dams at risk of failure (Lowry,

177   2003; Pohl, 2002; Ryan Bellmore et al., 2017). A core assumption of opportunistic

178   response is that any given barrier removal will result in river connectivity

179   improvements. While this may often be true for resident fish and aquatic species, the

180   extent to which long distance migratory fish, including diadromous salmon and eel, will

181   benefit largely depends on where a dam is located relative to other barriers. Removing

182   a dam above of an impassable barrier located downstream will provide no connectivity

183   gain for migratory species, even if the project is readily feasible. Accordingly,

184   opportunistic response has the potential to be extremely inefficient if followed

185   indiscriminately without taking into account important contextual considerations

186   (O'Hanley, 2011).

187   To avoid inefficiency, it is recommended that guidelines be adopted to ensure

188   some minimal return on investment (McKay et al., 2020). For example, a river

189   conservation organization could decide to focus efforts on minimally degraded rivers

190   or employ a simple rule-of-thumb of first removing barriers closest to the river mouth.

191   Basic standards such as these can help ensure an organization maintains an

192   emphasis on delivering positive outcomes rather than jumping at every opportunity

193   that comes along. On the other hand, as barriers tend to be spatially clustered (Jones

194   et al., 2019), the removal of an opportunistic barrier that may not in itself result in a

195   large return on investment may help rally support for the removal of other neighboring

196   barriers that do.

197

198   _Local knowledge & expert opinion_

199   Use of local knowledge about barriers together with input of experts from various fields

200   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 judgement comes from Europe. Many of the national agencies with statutory

226 responsibility for maintaining free passage for migratory fish lack any coherent

227 approach to barrier prioritization (Schäfer, 2021). Often, they rely on a strategy in

228 which regional authorities or local rivers trusts are tasked with coming up with a list of

229 high priority barriers in their respective region or catchment. The manner in which

230 priorities are arrived at is left to their discretion without any common set of criteria. To

231 compound the problem, species of interest across different regions/catchments are

232 not always the same. National level priorities, when there are any, are ultimately

233 derived by 'filtering' various regional priorities using some *ad-hoc* process which is not

234 repeatable or transparent, highlighting the weakness of using expert judgement alone

235 when working at supra-basin scales.

236

237 **5.1.2 Formal methods**

238 *Scoring & ranking*

239 Scoring and ranking is the most popular type of formal method used for prioritizing

240 barrier mitigation decisions (Hoenke et al., 2014; Kocovsky et al., 2009; Martin, 2019a;

241 Nunn and Cowx, 2012; Taylor and Love, 2003; WDFW, 2009). Here, barriers are

242 scored according to a set of assessment criteria, ranked in order of score, and then

243 selected for repair/removal based on rank until the budget is exhausted. Scoring

244 systems typically account for one or more of the following: (i) habitat quantity; (ii)

245 habitat quality; (iii) degree of improvement in fish passage as a result of mitigation;

246 and (iv) cost of mitigation. More sophisticated ones (Hoenke et al., 2014; Martin,

247 2019a; Nunn and Cowx, 2012) further account for the number and or passability of

248 downstream barriers, and can also deal with uncertainty. A widely employed scoring

249 and ranking approach is to use benefit-cost ratios, namely habitat gain divided by costs

250 of removal, with barriers then ranked from most to least cost-effective.

251   The appeal of scoring and ranking lies in its simplicity. Once barrier attributes

252   and weightings have been agreed upon, the results are simple to communicate and

253   decisions easy to explain. It is also flexible in that new attributes can be added or

254   modified as more data become available. The main disadvantage is that barriers are

255   treated independently from each other, without taking into account their spatial

256   relationship, and as number of studies have shown (O'Hanley et al., 2013; O'Hanley

257   and Tomberlin, 2005) this often produces poor quality solutions. Cumulative

258   passability (the degree to which fish and other aquatic organism can successfully pass

259   multiple barriers arranged in series) is invariably determined by the passability of

260   barriers downstream and upstream. Ignoring this, especially in the case of diadromous

261   fish, can result in proposals to mitigate barriers located above impassable downstream

262   barriers even though this would produce no habitat gain at all.

263   While more elaborate scoring systems are able to take into account barrier

264   spatial structure (e.g., number of downstream barriers), scoring and ranking suffers

265   from an even more fundamental shortcoming, which is that decisions about individual

266   barriers are made independently rather than in a coordinated manner. Scores are

267   calculated assuming that passabilities at other barriers are constant. Mitigation of

268   multiple barriers, however, produces non-additive or interactive changes in cumulative

269   passability. Put another way, the gain produced by mitigating a given barrier is not

270   fixed, but depends on whether other barriers downstream and upstream have or will

271   be mitigated as well. For this reason, scoring and ranking typically fails to find good

272   quality solutions (especially at low budgets), as it cannot deal with multiple barriers

273   simultaneously. In addition, stakeholder involvement is limited, although their opinions

274   can be used to set the weightings and find the barrier attributes of choice. There is

275   also no explicit consideration of uncertainty.

276 *GIS scenario analysis*

277 With GIS scenario analysis, various data layers and attributes are used as filters in a

278 geographic information system (sometimes web-based) to simulate the consequences

279 of acting on individual barriers or groups of them, typically by calculating simple

280 connectivity metrics like total reconnected stream distance in the upstream and or

281 downstream directions (Barrios, 2011; Martin, 2019a; Martin, 2019b; Martin and Apse,

282 2011; Martin et al., 2014). This information can subsequently be used to produce a

283 ranked list (often involving some sort of scoring and ranking procedure) of single

284 barrier interventions or compare different portfolios of barriers (one online tool is

285 available here: https://maps.freshwaternetwork.org/northeast/).

286 This method is visually appealing, easy to communicate and can be very

287 effective in conveying gains under various *what-if* scenarios (e.g., primary restoration

288 focus and budget). It is easy to scale up and can easily handle many data layers, many

289 of which may be publicly available. The limitations of this approach is that it requires

290 a GIS platform and appropriate expertise. It is sometimes limited to small spatial

291 domains involving a limited number of barriers due to the extent of coverage provided

292 by the data layers. Stakeholder involvement and uptake may also be low if the

293 implementation is not user-friendly or easily accessible online. Importantly, the choice

294 of attributes to use or consider can be very subjective, which hampers repeatability

295 and transparency. As with previous prioritization methods, there is no way of knowing

296 whether a particular barrier mitigation solution is cost-efficient.

297

298 *Graph theory*

299 Graph theory models overcome many of the limitations of scoring and ranking by

300 capturing the dendritic structure of rivers and spatial relationships of barrier networks.

301 In this way, they are able to account for the interactive effects of barrier mitigation on

302 cumulative passability. The application of graph theory involves two, interlinked steps.

303 First, a graph composed of nodes and arcs is created to represent a particular barrier

304 network. Second, a numerical index of some kind is calculated to measure the overall

305 degree of connectivity within a river network, thus making graph theory decidedly more

306 sophisticated than ad hoc GIS scenario analysis. Different indices have been devised

307 to suit specific fish dispersal and life-history needs, including diadromous and

308 potadromous fish.

309   One of the first and most well-known graph theory models developed for barrier

310 mitigation planning is the Dendritic Connectivity Index (DCI) proposed by (Cote et al.,

311 2009). To calculate DCI, a graph is constructed with barriers represented by nodes

312 and arcs connecting adjacent barriers. Other graph approaches (Erős et al., 2011;

313 Segurado et al., 2013) are distinctly different from DCI in that nodes represent stream

314 segments, while arcs designate whether or not stream segments are confluent with

315 one another. Two widely used indices for this alternative graph representation are the

316 Betweenness Centrality (BC) index and the Index of Connectivity (IIC). BC measures

317 the frequency with which a node (stream segment) falls within the shortest path

318 between pairs of nodes (stream segments) in a network. It attempts to quantify the

319 role steam segments serve as a "stepping stones." ICC, in contrast, provides an

320 overall measure of longitudinal connectivity and quantifies the importance of both

321 habitat availability and connectivity. For both BC and ICC, it is assumed that barriers

322 are either completely passable or completely impassable. This makes these indices

323 rather more limited than DCI in that they do not allow for partial barrier passability.

324   Graph theory models are noteworthy for taking a holistic view of river

325 connectivity (i.e., one that considers the spatial relationship of all barriers in the

326 catchment, rather than each barrier in isolation). Unlike with scoring and ranking, they

327 are specifically designed to incorporate the interactive effects of barrier mitigation, thus

328 allowing decisions to be made in a coordinated manner. Nonetheless, graph theory

329 models by themselves are merely *descriptive* – they do not provide any guidance as

330 to how barriers can be mitigated in a cost-efficient manner. This makes them useful

331 for carrying out simple *what-if* type analyses (similar to GIS scenario analysis)

332 involving questions like: How would longitudinal connectivity be affected by the

333 mitigation of this particular barrier or this set of barriers? For a given budget, it is

334 entirely up to the end-user to come up with a feasible portfolio of mitigation actions

335 that maximizes overall connectivity.

336

337 *Mathematical optimization*

338 The final and most sophisticated barrier prioritization method is mathematical

339 optimization, developed mostly over the last two decades (King and O'Hanley, 2016;

340 King et al., 2021; King et al., 2017; Kuby et al., 2005; Milt et al., 2018; Moody et al.,

341 2017; O'Hanley, 2011; O'Hanley et al., 2013; O'Hanley and Tomberlin, 2005). Unlike

342 other methods, which are generally descriptive, mathematical optimization is a

343 *prescriptive* approach that produces a recommended course of action. Like graph

344 theory, optimization is fully capable of accounting for the spatial structure of barrier

345 networks and the interactive effects of mitigation on river connectivity. Optimization

346 goes beyond graph theory, however, in being able to find an optimal or near optimal

347 portfolio of barrier removals to maximize longitudinal connectivity gains subject to

348 various constraints (e.g., a limited budget). This ensures the best possible use of

349 limited resources. The use of optimization has other advantages as well (Kemp and

350 O'Hanley, 2010), including greater transparency and repeatability, increased flexibility,

351 and explicit consideration of uncertainty. For example, the fact that optimization

352 methods rely on clear and objective criteria makes them more transparent and

353 repeatable than other methods. They also provide enormous flexibility by enabling

354 decision makers to balance multiple, possibly competing, environmental and

355 socioeconomic goals, like hydropower (Kuby et al., 2005), ecosystem productivity

356 (Zheng et al., 2009), dam safety (Zheng and Hobbs, 2013), fish abundance and

357 richness (King et al., 2021), recreation (Roy et al., 2018), potential threats from

358 invasive species (Milt et al., 2018), and climate change impacts (Farzaneh et al.,

359 2021). Even uncertainty can be incorporated into an optimization model in a coherent

360 fashion, allowing planners to effectively hedge against risk, including data limitation

361 related to the number and location of barriers (Ioannidou, 2017).

362 Besides being useful for strategically targeting high impact barriers within a

363 given area that yield the "biggest bang for the buck," optimization models can also be

364 used in a variety of other ways. For example, connectivity gain versus barrier

365 mitigation cost generally shows a pattern of diminishing return (King and O'Hanley,

366 2016; O'Hanley, 2011), whereby increases in connectivity become progressively

367 smaller with increased budget and eventually reach a plateau. Habitat gain versus

368 cost curves, however, are not always smooth; there may be critical thresholds, below

369 which connectivity gains may be small. Accordingly, optimization can be helpful in

370 identify appropriate levels of investment in barrier mitigation that are sufficient in

371 meeting defined planning goals. At the very least, optimization models are useful for

372 identifying potentially cost-efficient solutions that can form the basis for more detailed

373 modeling and fine-tuning later on.

374 Optimization, however, is not without drawbacks. It can be viewed as

375 excessively prescriptive (McKay et al., 2020) and tends to ignore local knowledge (Fox

376 et al., 2016), which may antagonize some stakeholders (Sneddon et al., 2017) and

377 make communication of results difficult. It also requires a high degree of mathematical

378 and computer programing expertise, although open source spatial planning software,

379 such as Marxan (Hermoso et al., 2021), and special purpose decision support

380 systems, such as OptiPass (O'Hanley, 2014) and the River Infrastructure Planning

381 (RIP) tool (O'Hanley et al., 2020) should facilitate more mainstreaming use of

382 optimization in barrier removal programs. Other downsides include the fact that (1)

383 small changes to budgets and project cost can result in markedly different solutions

384 since there is no guarantee that solutions will be nested (O'Hanley, 2011); (2) the

385 quality of solutions tends to be heavily reliant on the availability of complete and

386 accurate barrier location data; and (3) recommended solutions may require

387 cooperation of multiple barrier owners, which may or may not be easy to achieve. The

388 latter two criticisms generally apply to all prioritization methods. Others have also

389 argued that optimization may give a false impression of accuracy that simply does not

390 exist in real life projects. For example, an optimal portfolio of barriers to be removed

391 may no longer be 'optimal' if one or more of the selected barriers cannot be removed.

392   Regarding the issue of nestedness, this refers to the fact that barriers selected

393 for removal at one budget may not be selected at a higher budget. The reason for this

394 is that previously unaffordable or costly mitigation actions may suddenly become much

395 more attractive only when the budget is sufficiently high. Indeed, studies have found

396 that a single large budget may be more efficient than 'toping-up' annual budgets

397 totaling the same amount so that expensive, but high impact removals can be actioned

398 (Neeson et al., 2015). In some cases, however, solutions are often nested - at least

399 within certain budgets. For this reason, it is important to run optimization models

400 across multiple budgets to ascertain the degree of nestedness and where any budget

401 thresholds may occur, as well as when diminishing returns from barrier removal begin

402 to set in.

403   To address the risk of some targeted barriers becoming in effect "non-

404 removable," rigorous sensitivity analysis is recommended. Here, different "what-if"

405 barrier exclusion scenarios can be run to assess how robust an optimized solution

406 really is. Further research on this topic is warranted to better mitigate such a risk.

407   Taken together, optimization sets the gold standard for efficient barrier

408 mitigation planning. To be practical, however, it needs to factor in the constraints

409 imposed by uncertainties and opportunities. A hybrid system, therefore, is probably

410 best on the grounds of effectiveness and robustness.

411

412 **5.2 Barrier prioritization in practice**

413 An online questionnaire consisting of 6 questions was developed with *SurveyMonkey*

414 and sent to ~200 river restoration practitioners across Europe and North America

415 (drawn from our network and a list of registered attendees to a river connectivity

416 webinar). A total of 58 responses were received from 15 countries one month later in

417 July 2021 (Figure S1), representing a ~29% response rate.

418   Most organizations consulted (~60%) had a plan to achieve free-flowing river

419 status in their basins (Figure S2) and most (34%) used expert judgment, consultation

420 with stakeholders (17%), or a combination of methods (28%) to prioritize barriers for

421 mitigation. Only 12% used dedicated software or a specific algorithm (Figure S3).

422   The barrier attributes most frequently used by practitioners in barrier

423 prioritization were barrier ownership and rights, the results of field surveys, and the

424 obsolescence and conservation status of barriers. In contrast, flow data and the

425 biodiversity value of a catchment were considered less frequently (Figure S4). The

426   most important rational flagged by practitioners to prioritize barriers was to improve

427   fish passage, with cost being the least important one (Figure S5). In terms of desirable

428   features of a barrier prioritization software, practitioners highlighted the flexibility to

429   evaluate different scenarios and the ability to link with existing GIS databases as the

430   most important ones. Open source software and explicit consideration of uncertainty

431   were deemed to be least important (Figure S6).

432

433   **6. Prioritizing the smart way – Operational considerations and**

434   **recommendations**

435
436   **6.1 Prioritizing barrier removal versus prioritizing barrier mitigation**

437   A fundamental aspect of some river restoration programs is that funding may only be

438   available for barrier removal and may exclude other barrier mitigation alternatives,

439   such as construction of fish passes, reconnection of side channels, or culvert

440   replacement. For example, the Open Rivers Programme (ORP) has recently set aside

441   €42.5 million over six years specifically to remove physical barriers, not to build fish

442   passes or embark on other mitigating actions. Likewise, with its new Biodiversity

443   Strategy, the European Commission has the vision to reconnect 25,000 km of free

444   flowing rivers by 2030 and it is thought that this will be achieved primarily by targeting

445   barriers for removal. Similarly, American Rivers, WWF, Dam Removal Europe, and

446   other organizations and collaborative initiatives emphasize barrier removal, not just in

447   a figurative sense, but in a literal one (WWF, 2021). This needs to be incorporated into

448   the prioritization strategy, as not all barriers can necessarily be acted upon, only those

449   that can be removed. Therefore, the baseline situation is not the white canvass implicit

450   in most barrier prioritization exercises that aim to maximize connectivity in the most

451   efficient possible way, but one where there is only a small subset of obsolete barriers

452   that can be readily removed. Pilot data from Europe suggest that obsolete barriers

453   represent ~13% of all barriers, which may considerably simplify the search for

454   workable solutions, but also needs to be taken into account in the barrier prioritization

455   process. As depicted in Figure 2, most non-flow regulating barriers cannot easily be

456   removed, they can only be modified or replaced by something else, like a bridge in the

457   case of a culvert, which will incur additional costs and may rule them out from funding

458   for barrier removal schemes.

459

460   **6.2 Identifying the 'fragmentizers'**

461   River walkover surveys indicate that barriers are not distributed at random, they tend

462   to be clustered (Atkinson et al., 2020; Jones et al., 2019; Sun et al., 2020). This has

463   two important consequences. First, it means that barrier impacts on stream

464   fragmentation are less severe than would have been the case if barriers had been

465   distributed regularly or randomly (Diebel et al., 2015). It also means that a relatively

466   small proportion of barriers (call them 'fragmentizers') will likely have an

467   disproportionate large impact on fragmentation. These fragmentizers can be identified

468   and located using some of the prioritization methods outlined above and a targeted

469   approach can produce substantial gains in connectivity by acting on a relatively small

470   number of barriers (Figure 4). For example, in the Willamette River, USA, removing

471   just 8% of barriers would reconnect 52% of the basin (Kuby et al., 2005). Several

472   studies have shown that the removal of certain key barriers can result in

473   disproportionately high gains in connectivity (Hermoso et al., 2021), but that benefits

474   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' (Figure 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).

525   Some metrics of connectivity require accurate barrier coordinates and this can

526   be further compounded by inaccurate stream networks. For example, the only stream

527   network available at a pan-European scale (ECRINS) may underestimate stream

528   length by a factor of 3 because first and second order streams are poorly mapped

529   (Kristensen and Globevnik, 2014). There are also uncertainties about precise barrier

530   locations, which can introduce important errors when 'snapping' them onto an already

531   coarse river network.

532   Barrier removal planning must also contend with uncertainties related to the

533   potential spread of invasive species (Cooper et al., 2021; Hermoso et al., 2021; Jones

534   et al., 2021b; Muha et al., 2021) and with future demands for water resources

535   (Baumgartner et al., 2021; Duarte et al., 2021; Radinger and García-Berthou, 2020;

536   Tickner et al., 2020). Many would argue that the answer to resolving issues around

537   uncertainty is to gather more data before making a decision. Waiting for more

538   information, however, involves its own opportunity costs (Grantham et al., 2009) and

539   can lead to a 'paralysis by analysis' syndrome (Blanco, 2008). Acquiring new data is

540   often costly and time consuming; money spent on data collection could alternatively

541   be spent on further on-the-ground mitigation work. One also needs to consider that

542   while data are being gathered, species and ecosystems may continue to decline due

543   to stream fragmentation. Freshwater migratory fish have suffered a 93% decline in

544   Europe over the last 45 years, due in large part to increasing fragmentation (Deinet et

545   al., 2020), so waiting to collect more data to reduce uncertainties in river restoration

546   may not be an option due to the irreparable harm that may be caused.

547   In the context of decision making, the benefits of investing in data gathering

548   should be evaluated in terms of its potential to alter priorities and boost restoration

549   gains, not simply to refine inputs and build better models. Here, value of information

550   analysis might help with this challenge by rigorously examining trade-offs between the

551   cost and benefits of gathering additional data (Maxwell et al., 2015). More

552   fundamentally, we would argue that the best way to deal with uncertainty in the context

553   of barrier prioritization and planning is to embrace uncertainty. Such an approach

554   would encourage river restoration managers to: (1) explore in greater depth the extent

555   and potential significance of uncertainties; (2) communicate uncertainties more

556   effectively; and (3) adopt more flexible and adaptive strategies to cope with

557   uncertainty.

558   Adaptive planning (Cid et al., 2022), in particular, would go a long way toward hedging

559   risks while at the same time equip planners to take advantage of any opportunities

560   that may arise to achieve easy wins that align with overall objectives. But no matter

561   what prioritization approach is ultimately adopted, decision makers need to be mindful

562   that barrier priorities should not be set in stone. Change and the unexpected, both bad

563   and good, are sometimes forced upon even the most carefully laid plans. Planning,

564   therefore, needs to be ever agile and flexible enough to adapt.

565

566   **6.5 Accounting for natural barriers**

567   Few studies account for the location of natural barriers (i.e., falls) despite the fact that

568   these can have a dramatic effect on the optimal selection of barriers for removal

569   (Diebel et al., 2015). In general, the benefits of acting on barriers located in the

570   headwaters are lessened by their proximity to natural fragmented habitats and the

571   smaller length of any upstream gains (Birnie-Gauvin et al., 2017; Duarte et al., 2021).

572   While this may not matter for sediment transport or whole-river processes, natural

573   features affect the distribution of fish species and what can be gained by barrier

574   removal. Most barrier prioritization studies lack information on natural barriers and

575   even when they do, it is assumed that they have no effect on connectivity (O'Hanley,

576   2011), which may not be the case. For example, species richness typically decreases

577   as one moves upstream within a river network, while natural fragmentation increases

578   (Vannote et al., 1980), so the benefits of acting on headwater infrastructures may

579   lessen. Missing information on the location of natural barriers can, to some extent, be

580   overcome by considering channel slope, as steep gradients are typically unsuitable

581   for many fish species. Gradient thresholds for migratory salmonids, for example,

582   typically range between 2 and 16% (Finn et al., 2021; Hendry and Cragg-Hine, 2003)

583   and are much lower for weaker swimmers (Legalle et al., 2005).

584

585   **6.6 Future-proofing barrier removal and the do-nothing option**

586   All barriers have a finite life span and proper maintenance is essential but also costly

587   (Neeson et al., 2015). Opportunities presented by barrier obsolescence must be

588   weighed against the *do-nothing* option and the likelihood of structural failure. Under a

589   scenario of more extreme weather events, investing in removing derelict or partially

590   breached structures may not always be cost-effective if it merely brings the process

591   forward by a few years. There is, therefore, a need to future-proof interventions.

592   Future-proofing barrier removal is also important in the face of climate change

593   because the impact of barriers for species depends on future water levels and river

594   flows (Zhao et al., 2021). In Europe, barrier impacts are expected to worsen in

595   countries where climate will get drier and flows are expected to decrease (e.g., the

596   Mediterranean region) but will lessen in places expected to become wetter (e.g.,

597   Scandinavia (Duarte et al., 2021)).

598

599

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References

Athayde, S., Duarte, C.G., Gallardo, A.L., Moretto, E.M., Sangoi, L.A., Dibo, A.P.A., Siqueira-Gay, J., Sánchez, L.E., 2019. Improving policies and instruments to address cumulative impacts of small hydropower in the Amazon. Energy Policy. 132, 265-271.

Atkinson, S., Bruen, M., JJ, O.S., Turner, J.N., Ball, B., Carlsson, J., Bullock, C., Casserly, C.M., Kelly-Quinn, M., 2020. An inspection-based assessment of obstacles to salmon, trout, eel and lamprey migration and river channel connectivity in Ireland. Sci. Total Environ. 719, 137215.

Barrios, J., 2011. Fish Passage Decision Support System: an Effective Tool for Planning Fish Passage Restoration at Multiple Geographic Scales, American Fisheries Society 140th Annual Meeting, Pittsburgh.

Baumgartner, L., Marsden, T., Duffy, D., Horta, A., Ning, N., 2021. Optimizing efforts to restore aquatic ecosystem connectivity requires thinking beyond large dams. Environmental Research Letters.

Bednarek, A.T., 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management. 27, 803-814.

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuysen, A., Birnie-Gauvin, K., Bussettini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernández, S., Fernandez Garrido, P., Garcia-Vazquez, E., Garrido, S., Giannico, G., Gough, P., Jepsen, N., Jones, P.E., Kemp, P., Kerr, J., King, J., Łapińska, M., Lázaro, G., Lucas, M.C., Marcello, L., Martin, P., McGinnity, P., O'Hanley, J., Olivo del Amo, R., Parasiewicz, P., Pusch, M., Rincon, G., Rodriguez, C., Royte, J., Schneider, C.T., Tummers, J.S., Vallesi, S., Vowles, A., Verspoor, E., Wanningen, H., Wantzen, K.M., Wildman, L., Zalewski, M., 2020. More than one million barriers fragment Europe's rivers. Nature. 588, 436-441.

Birnie-Gauvin, K., Aarestrup, K., Riis, T.M.O., Jepsen, N., Koed, A., 2017. Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers, and its implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems. 27, 1345-1349.

Blanco, J., 2008. Integrated water resource management in Colombia: paralysis by analysis? International Journal of Water Resources Development. 24, 91-101.

Branco, P., Segurado, P., Santos, J.M., Ferreira, M.T., 2014. Prioritizing barrier removal to improve functional connectivity of rivers. Journal of Applied Ecology. 51, 1197-1206.

Buchanan, B.P., Sethi, S.A., Cuppett, S., Lung, M., Jackman, G., Zarri, L., Duvall, E., Dietrich, J., Sullivan, P., Dominitz, A., Archibald, J.A., Flecker, A., Rahm, B.G., 2022. A machine learning approach to identify barriers in stream networks demonstrates high prevalence of unmapped riverine dams. J. Environ. Manag. 302, 113952.

Carpenter, S.R., Stanley, E.H., Vander Zanden, M.J., 2011. State of the world's freshwater ecosystems: physical, chemical, and biological changes. Annual Review of Environment and Resources. 36, 75-99.

Cid, N., Erős, T., Heino, J., Singer, G., Jähnig, S.C., Cañedo-Argüelles, M., Bonada, N., Sarremejane, R., Mykrä, H., Sandin, L., Paloniemi, R., Varumo, L., Datry, T., 2022. From meta-system theory to the sustainable management of rivers in the Anthropocene. Frontiers in Ecology and the Environment. 20, 49-57.

652   Consuegra, S., O'Rorke, R., Rodriguez-Barreto, D., Fernandez, S., Jones, J., Garcia
653   de Leaniz, C., 2021. Impacts of large and small barriers on fish assemblage
654   composition assessed using environmental DNA metabarcoding. Science of
655   The Total Environment 148054.
656   Cooper, A.R., Infante, D.M., O'Hanley, J.R., Yu, H., Neeson, T.M., Brumm, K.J.,
657   2021. Prioritizing native migratory fish passage restoration while limiting the
658   spread of invasive species: A case study in the Upper Mississippi River.
659   Science of The Total Environment, 148317.
660   Costea, G., Pusch, M.T., Bănăduc, D., Cosmoiu, D., Curtean-Bănăduc, A., 2021. A
661   review of hydropower plants in Romania: Distribution, current knowledge, and
662   their effects on fish in headwater streams. Renewable and Sustainable
663   Energy Reviews. 145, 111003.
664   Cote, D., Kehler, D.G., Bourne, C., Wiersma, Y.F., 2009. A new measure of
665   longitudinal connectivity for stream networks. Landscape Ecology. 24, 101-
666   113.
667   Deinet, S., Scott-Gatty, K., Rotton, H., Twardek, W.M., Marconi, V., McRae, L.,
668   Baumgartner, L.J., Brink, K., Claussen, J.E., Cooke, S.J., Darwall, W.,
669   Eriksson, B.K., Garcia de Leaniz, C., Hogan, Z., Royte, J., Silva, L.G.M.,
670   Thieme, M.L., Tickner, D., Waldman, J., Wanningen, H., Weyl, O.L.F.,
671   Berkhuysen, A., 2020. The Living Planet Index (LPI) for migratory freshwater
672   fish. Technical Report. World Fish Migration Foundation, Groningen, The
673   Netherlands, pp. 30.
674   Diebel, M.W., Fedora, M., Cogswell, S., O'Hanley, J.R., 2015. Effects of road
675   crossings on habitat connectivity for stream-resident fish. River Research and
676   Applications. 31, 1251-1261.
677   Duarte, G., Segurado, P., Haidvogl, G., Pont, D., Ferreira, M.T., Branco, P., 2021.
678   Damn those damn dams: Fluvial longitudinal connectivity impairment for
679   European diadromous fish throughout the 20th century. Sci. Total Environ.
680   761, 143293.
681   Erős, T., Schmera, D., Schick, R., 2011. Network thinking in riverscape conservation
682   – A graph-based approach. Biological Conservation 144, 184-192.
683   Farzaneh, M.A., Rezapour, S., Fovargue, R., Neeson, T.M., 2021. Stochastic
684   mathematical models to balance human and environmental water needs and
685   select the best conservation policy for drought-prone river basins. Journal of
686   Cleaner Production. 291, 125230.
687   Finn, R.J., Chalifour, L., Gergel, S.E., Hinch, S.G., Scott, D.C., Martin, T.G., 2021.
688   Quantifying lost and inaccessible habitat for Pacific salmon in Canada's Lower
689   Fraser River. Ecosphere. 12, e03646.
690   Fox, C.A., Magilligan, F.J., Sneddon, C.S., 2016. "You kill the dam, you are killing a
691   part of me": Dam removal and the environmental politics of river restoration.
692   Geoforum. 70, 93-104.
693   Grantham, H.S., Wilson, K.A., Moilanen, A., Rebelo, T., Possingham, H.P., 2009.
694   Delaying conservation actions for improved knowledge: how long should we
695   wait? Ecol. Lett. 12, 293-301.
696   Grizzetti, B., Pistocchi, A., Liquete, C., Udias, A., Bouraoui, F., van de Bund, W.,
697   2017. Human pressures and ecological status of European rivers. Sci Rep. 7,
698   205.
699   Guetz, K., 2020. Dam removal prioritization in the west: An optimization approach for
700   river restoration and conservation. Northern Arizona University.

Heinz Center, 2002. Dam Removal: Science and Decision Making. Heinz Center for Science, Economics, and the Environment, Washington, DC.

Hendry, K., Cragg-Hine, D., 2003. Ecology of the Atlantic Salmon, Conserving Natura 2000 Rivers Ecology Series. English Nature, Peterborough, UK, pp. 36.

Hermoso, V., Clavero, M., Filipe, A.F., 2021. An accessible optimisation method for barrier removal planning in stream networks. Science of The Total Environment. 752, 141943.

Hoenke, K.M., Kumar, M., Batt, L., 2014. A GIS based approach for prioritizing dams for potential removal. Ecological Engineering. 64, 27-36.

Ioannidou, C., 2017. Optimising river infrastructure placement and mitigation decisions. University of Kent.

Ioannidou, C., O'Hanley, J.R., 2019. The importance of spatiotemporal fish population dynamics in barrier mitigation planning. Biological Conservation. 231, 67-76.

Januchowski-Hartley, S., R. , White, J., C. , Pawar, S., K. , Januchowski-Hartley, F., A. , England, J., 2021. Addressing road-river infrastructure gaps using a model-based approach. Environmental Research: Infrastructure and Sustainability.

Januchowski-Hartley, S.R., Jezequel, C., Tedesco, P.A., 2019. Modelling built infrastructure heights to evaluate common assumptions in aquatic conservation. Journal of environmental management. 232, 131-137.

Jones, J., Garcia de Leaniz, C., Belletti, B., Börger, L., Segura, G., Bizzi, S., van de Bund, W., 2020a. Quantifying river fragmentation from local to continental scales: data management and modelling methods. Authorea (pre-print)

Jones, J., Borger, L., Tummers, J., Jones, P., Lucas, M., Kerr, J., Kemp, P., Bizzi, S., Consuegra, S., Marcello, L., Vowles, A., Belletti, B., Verspoor, E., Van de Bund, W., Gough, P., Garcia de Leaniz, C., 2019. A comprehensive assessment of stream fragmentation in Great Britain. Sci. Tot. Env. 673, 756-762.

Jones, P.E., Consuegra, S., Börger, L., Jones, J., Garcia de Leaniz, C., 2020b. Impacts of artificial barriers on the connectivity and dispersal of vascular macrophytes in rivers: A critical review. Freshwater Biology. 65, 1165-1180.

Jones, P.E., Champneys, T., Vevers, J., Börger, L., Svendsen, J.C., Consuegra, S., Jones, J., Garcia de Leaniz, C., 2021a. Selective effects of small barriers on river-resident fish. Journal of Applied Ecology. 58, 1487-1498.

Jones, P.E., Tummers, J.S., Galib, S.M., Woodford, D.J., Hume, J.B., Silva, L.G.M., Braga, R.R., Garcia de Leaniz, C., Vitule, J.R.S., Herder, J.E., Lucas, M.C., 2021b. The use of barriers to limit the spread of aquatic invasive animal species: a global review. Frontiers in Ecology and Evolution. 9

Jumani, S., Deitch, M.J., Kaplan, D., Anderson, E.P., Krishnaswamy, J., Lecours, V., Whiles, M.R., 2020. River fragmentation and flow alteration metrics: a review of methods and directions for future research. Environmental Research Letters. 15.

Kemp, P.S., O'Hanley, J.R., 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. Fisheries Management and Ecology. 17, 297-322.

King, S., O'Hanley, J.R., 2016. Optimal fish passage barrier removal—revisited. River Research and Applications. 32, 418-428.

King, S., O'Hanley, J.R., Fraser, I., 2021. How to choose? A bioeconomic model for optimizing river barrier mitigation actions. Ecological Economics. 181, 106892.

King, S., O'Hanley, J.R., Newbold, L.R., Kemp, P.S., Diebel, M.W., Heino, J., 2017. A toolkit for optimizing fish passage barrier mitigation actions. Journal of Applied Ecology. 54, 599-611.

Kocovsky, P.M., Ross, R.M., Dropkin, D.S., 2009. Prioritizing removal of dams for passage of diadromous fishes on a major river system. River Research and Applications. 25, 107-117.

Kristensen, Globevnik, 2014. European small water bodies. Biology and Environment: Proceedings of the Royal Irish Academy. 114B.

Kuby, M.J., Fagan, W.F., ReVelle, C.S., Graf, W.L., 2005. A multiobjective optimization model for dam removal: an example trading off salmon passage with hydropower and water storage in the Willamette basin. Advances in Water Resources. 28, 845-855.

Legalle, M., Santoul, F., Figuerola, J., Mastrorillo, S., Céréghino, R., 2005. Factors influencing the spatial distribution patterns of the bullhead (Cottus gobio L., Teleostei Cottidae): a multi-scale study. Biodivers. Conserv. 14, 1319-1334.

Lowry, W.R., 2003. Dam politics: Restoring America's rivers. Georgetown University Press.

Maavara, T., Lauerwald, R., Regnier, P., Van Cappellen, P., 2017. Global perturbation of organic carbon cycling by river damming. Nature communications. 8, 1-10.

Maavara, T., Chen, Q., Van Meter, K., Brown, L.E., Zhang, J., Ni, J., Zarfl, C., 2020. River dam impacts on biogeochemical cycling. Nature Reviews Earth & Environment. 1, 103-116.

Martin, E.H., 2019a. Assessing and prioritizing barriers to aquatic connectivity in the Eastern United States. JAWRA Journal of the American Water Resources Association. 55, 401-412.

Martin, E.H., 2019b. Chesapeake fish passage prioritization: An assessment of dams in the Chesapeake Bay watershed., pp. 135.

Martin, E.H., Apse, C.D., 2011. Northeast aquatic connectivity: An assessment of dams on northeastern rivers. The Nature Conservancy, Eastern Freshwater Program, pp. 102.

Martin, E.H., Hoenke, K., Granstaff, E., Barnett, A., Kauffman, J., Robinson, S., Apse, C.D., 2014. SEACAP: Southeast aquatic connectivity assessment project: Assessing the ecological impact of dams on southeastern rivers pp. 99.

Maxwell, S.L., Rhodes, J.R., Runge, M.C., Possingham, H.P., Ng, C.F., McDonald-Madden, E., 2015. How much is new information worth? Evaluating the financial benefit of resolving management uncertainty. Journal of Applied Ecology. 52, 12-20.

McKay, S., Cooper, A., Diebel, M., Elkins, D., Oldford, G., Roghair, C., Wieferich, D., 2017. Informing watershed connectivity barrier prioritization decisions: a synthesis. River Research and Applications. 33, 847-862.

McKay, S.K., Martin, E.H., McIntyre, P.B., Milt, A.W., Moody, A.T., Neeson, T.M., 2020. A comparison of approaches for prioritizing removal and repair of barriers to stream connectivity. River Research and Applications. 36, 1754-1761.

Milt, A.W., Diebel, M.W., Doran, P.J., Ferris, M.C., Herbert, M., Khoury, M.L., Moody, A.T., Neeson, T.M., Ross, J., Treska, T., O'Hanley, J.R., Walter, L., Wangen,

S.R., Yacobson, E., McIntyre, P.B., 2018. Minimizing opportunity costs to aquatic connectivity restoration while controlling an invasive species. Conservation biology : the journal of the Society for Conservation Biology. 32, 894-904.

Moody, A.T., Neeson, T.M., Wangen, S., Dischler, J., Diebel, M.W., Milt, A., Herbert, M., Khoury, M., Yacobson, E., Doran, P.J., 2017. Pet project or best project? Online decision support tools for prioritizing barrier removals in the Great Lakes and beyond. Fisheries. 42, 57-65.

Morden, R., Horne, A., Bond, N.R., Nathan, R., Olden, J.D., 2022. Small artificial impoundments have big implications for hydrology and freshwater biodiversity. Frontiers in Ecology and the Environment. n/a.

Muha, T.P., Rodriguez-Barreto, D., O'Rorke, R., Garcia de Leaniz, C., Consuegra, S., 2021. Using eDNA metabarcoding to monitor changes in fish community composition after barrier removal. Frontiers in Ecology and Evolution. 9.

Mulligan, M., Lehner, B., Zarfl, C., Thieme, M., Beames, P., van Soesbergen, A., Higgins, J., Januchowski-Hartley, S.R., Brauman, K.A., De Felice, L., Wen, Q., Garcia de Leaniz, C., Belletti, B., Mandle, L., Yang, X., Wang, J., Mazany-Wright, N., 2021. Global Dam Watch: Curated data and tools for management and decision making. Environmental Research: Infrastructure and Sustainability.

Neeson, T.M., Ferris, M.C., Diebel, M.W., Doran, P.J., O'Hanley, J.R., McIntyre, P.B., 2015. Enhancing ecosystem restoration efficiency through spatial and temporal coordination. Proceedings of the National Academy of Sciences of the United States of America. 112, 6236-6241.

Neeson, T.M., Moody, A.T., O'Hanley, J.R., Diebel, M., Doran, P.J., Ferris, M.C., Colling, T., McIntyre, P.B., 2018. Aging infrastructure creates opportunities for cost-efficient restoration of aquatic ecosystem connectivity. Ecol Appl. 28, 1494-1502.

Nunn, A., Cowx, I., 2012. Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys. Ambio. 41, 402-409.

O'Hanley, J.R., 2011. Open rivers: barrier removal planning and the restoration of free-flowing rivers. Journal of environmental management. 92, 3112-3120.

O'Hanley, J.R., Wright, J., Diebel, M., Fedora, M.A., Soucy, C.L., 2013. Restoring stream habitat connectivity: a proposed method for prioritizing the removal of resident fish passage barriers. J. Environ. Manag. 125, 19-27.

O'Hanley, J., Feierfeil, T., Kauppert, K., 2020. DST1. River Infrastructure Planning Tool (RIP) AMBER Policy Brief 2: Tools for managing and restoring connectivity in European rivers. AMBER - EU Horizon 2020 project (grant no. 689682), pp. 9-10.

O'Hanley, J.R., 2014. OptiPass: The migratory fish passage optimization tool, version 1.0 User manual, Portland, OR (USA), pp. 48

O'Hanley, J.R., Tomberlin, D., 2005. Optimizing the removal of small fish passage barriers. Environmental Modeling & Assessment. 10, 85-98.

Palmer, M., Ruhi, A., 2019. Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. Science. 365.

Perera, D., Smakhtin, V., Williams, S., North, T., Curry, A., 2021. Ageing Water Storage Infrastructure: An Emerging Global Risk. UNU-INWEH Report Series. 11.

848 Pohl, M.M., 2002. Bringing down our dams: Trends in American dam removal
849   rationales Journal of the American Water Resources Association. 38, 1511-
850   1519.
851 Radinger, J., García-Berthou, E., 2020. The role of connectivity in the interplay
852   between climate change and the spread of alien fish in a large Mediterranean
853   river. Global change biology. 26, 6383-6398.
854 Robertson, B.A., Hutto, R.L., 2006. A framework for understanding ecological traps
855   and an evaluation of existing evidence. Ecology. 87, 1075-1085.
856 Rodeles, A.A., Leunda, P.M., Elso, J., Ardaiz, J., Galicia, D., Miranda, R., 2019.
857   Consideration of habitat quality in a river connectivity index for anadromous
858   fishes. Inland Waters. 9, 278-288.
859 Roy, S.G., Uchida, E., de Souza, S.P., Blachly, B., Fox, E., Gardner, K., Gold, A.J.,
860   Jansujwicz, J., Klein, S., McGreavy, B., 2018. A multiscale approach to
861   balance trade-offs among dam infrastructure, river restoration, and cost.
862   Proceedings of the National Academy of Sciences. 115, 12069-12074.
863 Ryan Bellmore, J., Duda, J.J., Craig, L.S., Greene, S.L., Torgersen, C.E., Collins,
864   M.J., Vittum, K., 2017. Status and trends of dam removal research in the
865   United States. Wiley Interdisciplinary Reviews: Water. 4, e1164.
866 Schäfer, T., 2021. Legal Protection Schemes for Free-Flowing Rivers in Europe: An
867   Overview. Sustainability. 13, 6423.
868 Segurado, P., Branco, P., Ferreira, M.T., 2013. Prioritizing restoration of structural
869   connectivity in rivers: a graph based approach. Landscape Ecology. 28, 1231-
870   1238.
871 Seliger, C., Zeiringer, B., 2018. River Connectivity, habitat fragmentation and related
872   restoration measures. in: Schmutz, S., Sendzimir, J. (Eds.), Riverine
873   Ecosystem Management. Springer Open, Cham, Switzerland, pp. 171-186.
874 Seliger, C., Scheikl, S., Schmutz, S., Schinegger, R., Fleck, S., Neubarth, J., Walder,
875   C., Muhar, S., 2016. Hy: Con: a strategic tool for balancing hydropower
876   development and conservation needs. River Research and Applications. 32,
877   1438-1449.
878 Sneddon, C., Magilligan, F., Fox, C., 2017. Science of the dammed: Expertise and
879   knowledge claims in contested dam removals. Water Alternatives. 10, 677.
880 Stanley, E.H., Doyle, M.W., 2003. Trading off: the ecological effects of dam removal.
881   Frontiers in Ecology and the Environment. 1, 15-22.
882 Sun, J., Galib, S.M., Lucas, M.C., 2020. Are national barrier inventories fit for stream
883   connectivity restoration needs? A test of two catchments. Water and
884   Environment Journal. 34, 791-803.
885 Taylor, R.N., Love, M., 2003. California Salmonid Stream Habitat Restoration
886   Manual–Part IX Fish Passage Evaluation at Stream Crossings. California
887   Department of Fish and Game Sacramento, CA.
888 Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E.,
889   Cooke, S.J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K.,
890   Jones, T., Leclere, D., Lynch, A.J., Leonard, P., McClain, M.E., Muruven, D.,
891   Olden, J.D., Ormerod, S.J., Robinson, J., Tharme, R.E., Thieme, M., Tockner,
892   K., Wright, M., Young, L., 2020. Bending the Curve of Global Freshwater
893   Biodiversity Loss: An Emergency Recovery Plan. Bioscience. 70, 330-342.
894 Tullos, D.D., Collins, M.J., Bellmore, J.R., Bountry, J.A., Connolly, P.J., Shafroth,
895   P.B., Wilcox, A.C., 2016. Synthesis of common management concerns
896   associated with dam removal. JAWRA Journal of the American Water
897   Resources Association. 52, 1179-1206.

898 Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980.
899   The river continuum concept. Canadian journal of fisheries and aquatic
900   sciences. 37, 130-137.
901 Wagner, B., Hauer, C., Habersack, H., 2019. Current hydropower developments in
902   Europe. Current Opinion in Environmental Sustainability. 37, 41-49.
903 WDFW, 2009. Fish passage barrier and surface water diversion screening
904   assessment and prioritization manual. Washington Department of Fish and
905   Wildlife (WDFW), Olympia, WA.
906 Weiter, R.L., 2014. Priotization of Fish Passage Projects, Fish Passage Workshop
907   Amherst.
908 Weiter, R.L., 2015. Prioritizing Mitigation of Road-Stream Crossings for Resident
909   Aquatic Organisms by Accounting for Habitat Quantity, Quality, and
910   Accessibility, Department of Civil and Environmental Engineering University of
911   Massachusetts Amherst, MA
912 World Commission on Dams, 2000. Dams and development: A new framework for
913   decision-making: The report of the world commission on dams. Earthscan,
914   Abingdon, UK.
915 WWF, 2021. The potential of barrier removal to reconnect Europe's rivers, pp. 21.
916 Zaidel, P.A., Roy, A.H., Houle, K.M., Lambert, B., Letcher, B.H., Nislow, K.H., Smith,
917   C., 2021. Impacts of small dams on stream temperature. Ecological
918   Indicators. 120, 106878.
919 Zhao, Y., Liu, S., Shi, H., 2021. Impacts of dams and reservoirs on local climate
920   change: a global perspective. Environmental Research Letters. 16, 104043.
921 Zheng, P.Q., Hobbs, B.F., 2013. Multiobjective portfolio analysis of dam removals
922   addressing dam safety, fish populations, and cost. Journal of Water
923   Resources Planning and Management. 139, 65-75.
924 Zheng, P.Q., Hobbs, B.F., Koonce, J.F., 2009. Optimizing multiple dam removals
925   under multiple objectives: Linking tributary habitat and the Lake Erie
926   ecosystem. Water Resources Research. 45.

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).

Trait	Prioritization method					
	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)

934 **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

935

936   **Figure legends**

937

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

939

940   **Figure 2.** Characteristics of different barrier types and how these can affect

941   decisions about barrier removal. The colour represents the ranking of each trait (note

942   these are merely indicative).

943

944   **Figure 3.** Classification of the six main barrier prioritization methods according to

945   their complexity and type of approach. OR - opportunistic response; LK - local

946   knowledge & expert opinion; SR - scoring and ranking; GIS - GIS scenario analysis;

947   GT – graph theory; MO - mathematical optimization.

948

949   **Figure 4.** Stream barriers are not randomly distributed, they tend to be found in

950   clusters (barriers 1-4). Acting on clusters will not normally yield significant gains,

951   unless all barriers in a cluster are mitigated or removed (top). However, acting on

952   some isolated barriers such as barrier 5 (a 'fragmentizer', bottom) may bring about

953   large gains in connectivity and be more cost-effective. These barriers can be

954   identified and removed, or be included in a strategic portfolio when the opportunity

955   for removal arises.

956

957   **Figure 5.** Mapping of barrier removal projects according to opportunities, cost and

958   gains can help locate the 'low hanging fruit'. Projects that produce limited gains are

959   regarded as 'inedible', regardless of what the opportunity or costs might be. Projects

960   that can achieve high connectivity gains at low costs may be 'green' if the

961 opportunity for removal is not quite there; these may ripen into 'sweet' fruit with time

962 and stakeholder pressure. Some projects could produce substantial gains but they

963 are too expensive and therefore are 'out of reach'. Only barriers that can readily be

964 removed and that can be expected to produce significant connectivity gains at low

965 cost are viewed as 'low hanging fruit'.

966

967 **Figure S1.** Distribution of responses to the barrier prioritization questionnaire by

968 country.

969

970 **Figure S2.** Responses to Q2 of the questionnaire on barrier prioritization methods in

971 relation to planning for free-flowing rivers.

972

973 **Figure S3.** Responses to Q3 of the questionnaire in relation to methods used for

974 barrier prioritization.

975

976 **Figure S4.** Responses to Q4 of the questionnaire in relation to information used for

977 barrier prioritization. The numbers above each answer indicate the mean support for

978 each metric on a five-point Likert scale (0-4), with the highest inferred support shown

979 in green and the lowest support in red.

980

981 **Figure S5.** Responses to Q5 of the questionnaire in relation to criteria used for

982 barrier prioritization. The numbers above each answer indicate the support for each

983 criteria on a five-point Likert scale (0-4), with the highest inferred support shown in

984 green and the lowest support in red.

985 **Figure S6.** Responses to Q6 of the questionnaire in relation to desirable features of

986 barrier prioritization software. The numbers above each answer indicate the support

987 for each criteria on a five-point Likert scale (0-4), with the highest inferred support

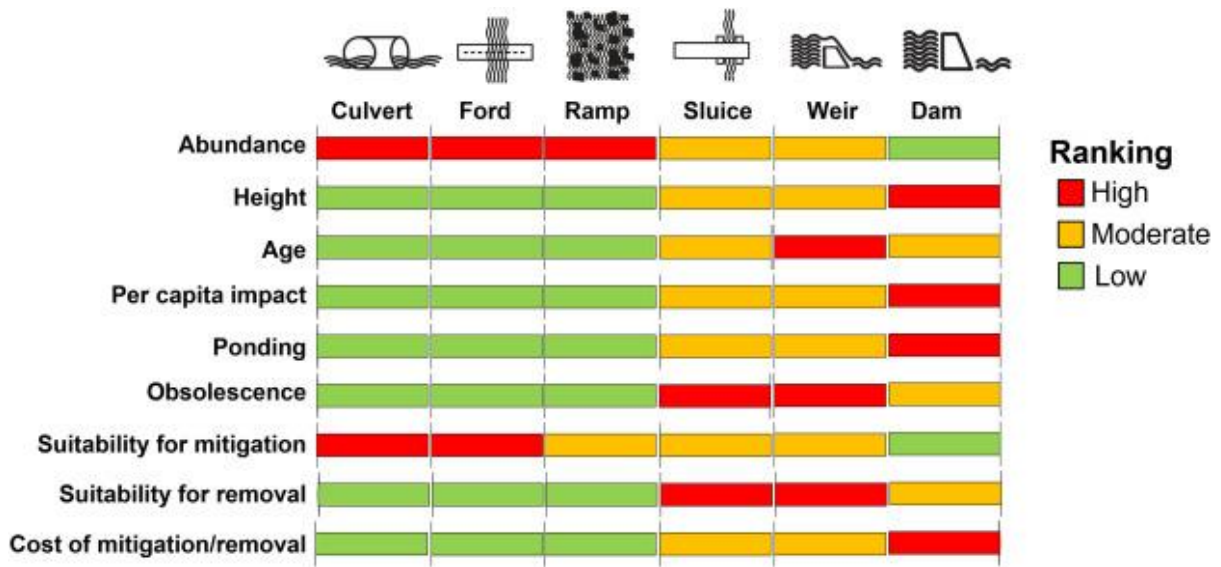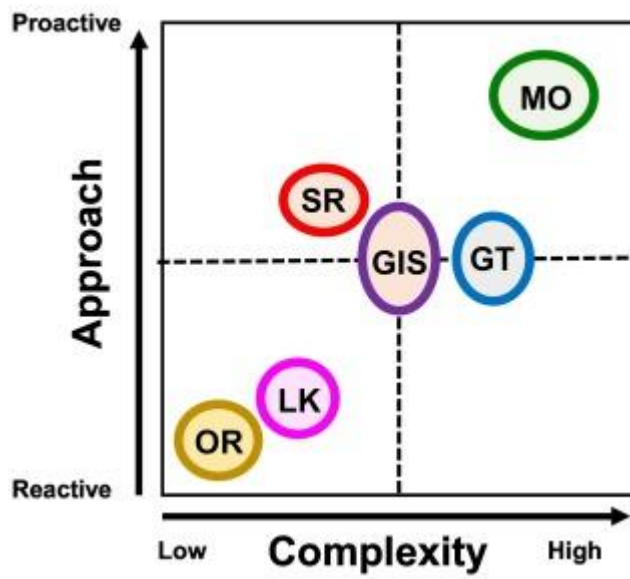988 shown in green and the lowest support in red.

989

990   [FIGURE 1]
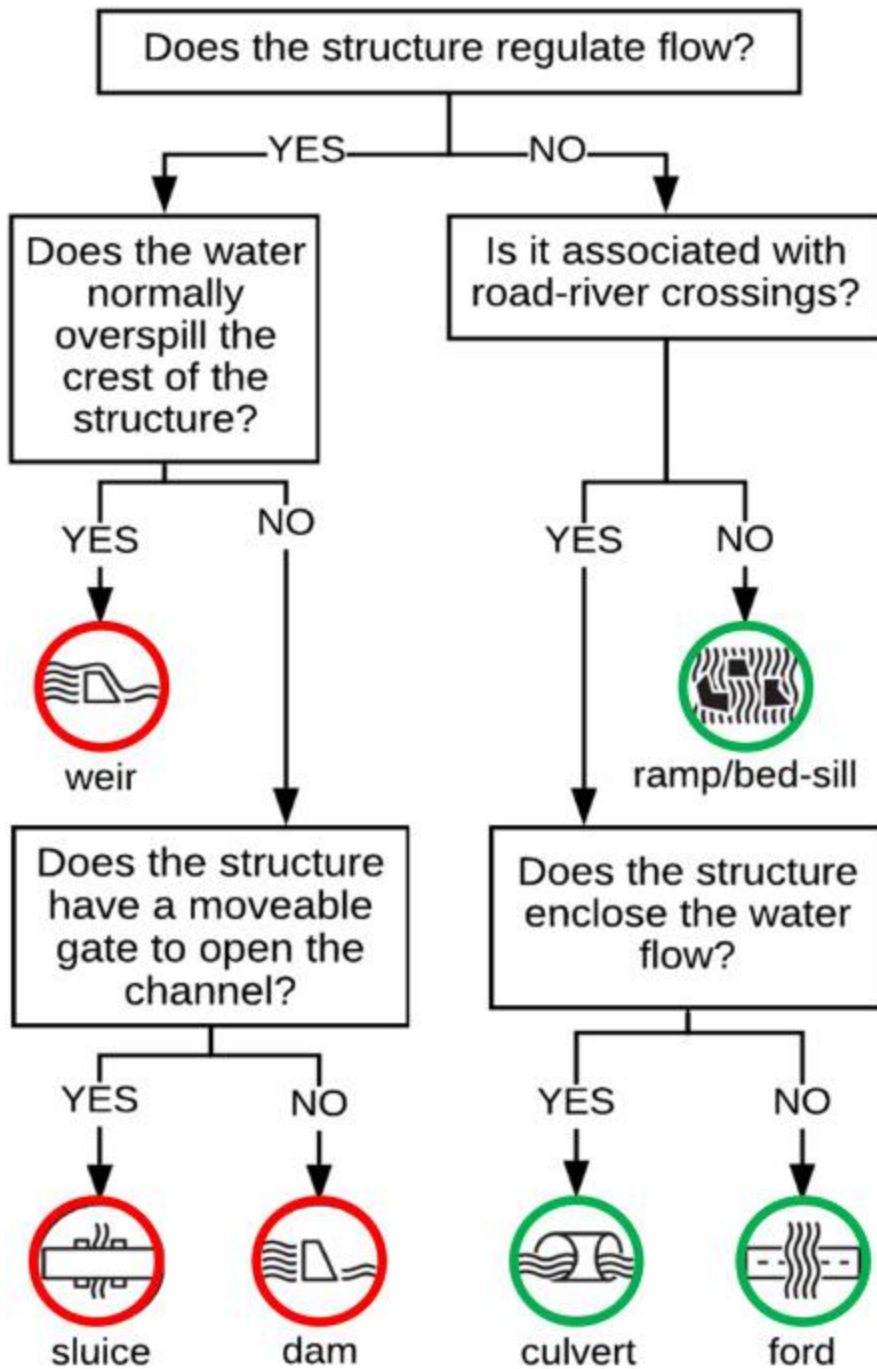
993   [FIGURE 2]

994

995

996   [FIGURE 3]

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999 [FIGURE 4]
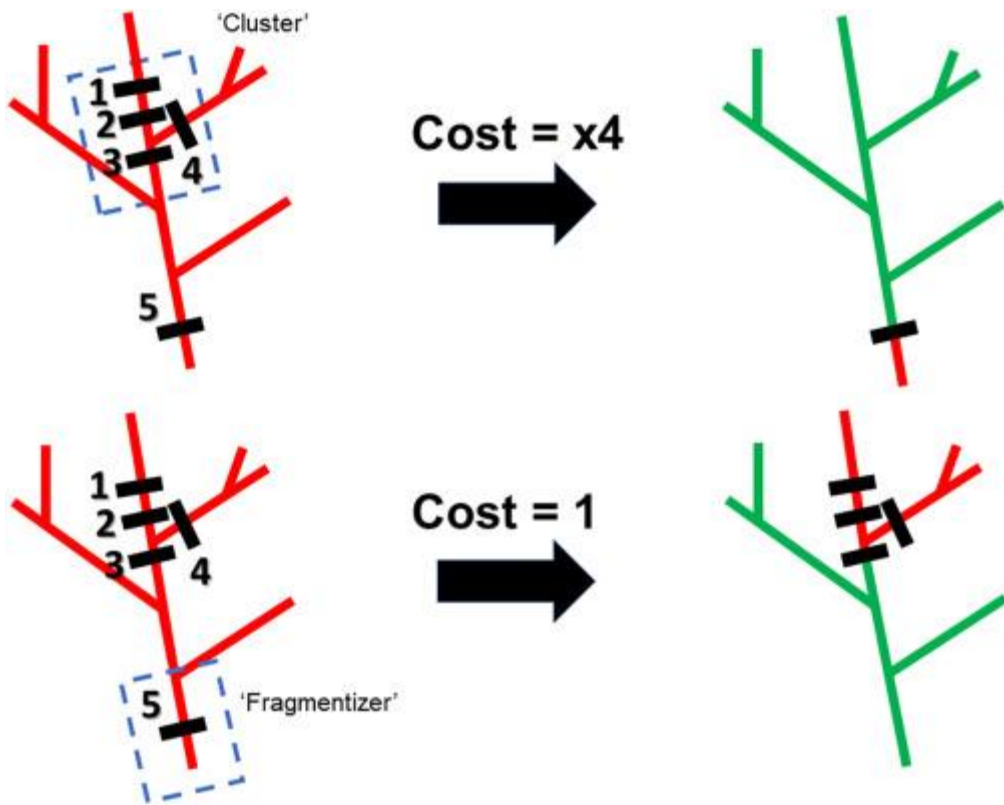
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1001

1002 [FIGURE 5]

1003

1004

1005   [FIGURE S1]
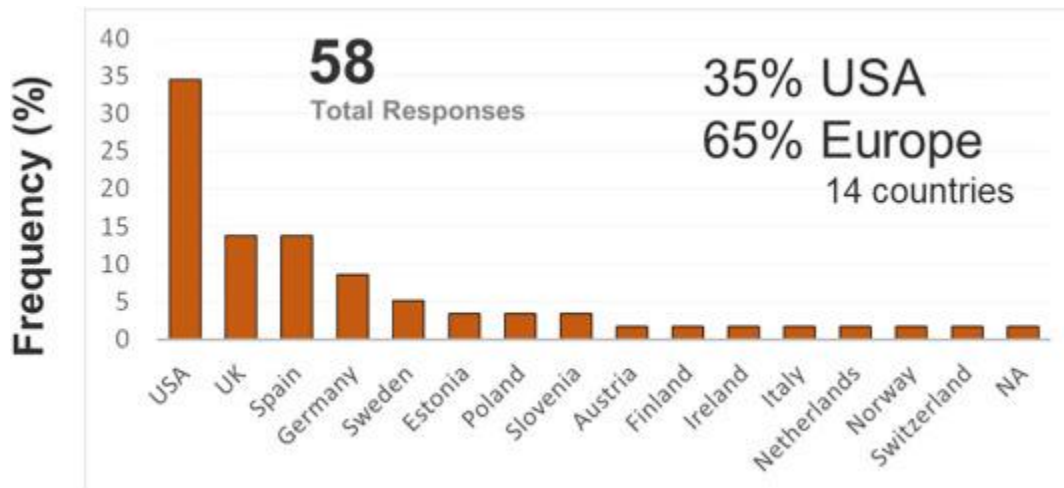
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1007

1008   [FIGURE S2]

Q2: Does your organization have a plan for achieving free-flowing rivers in your river basin?
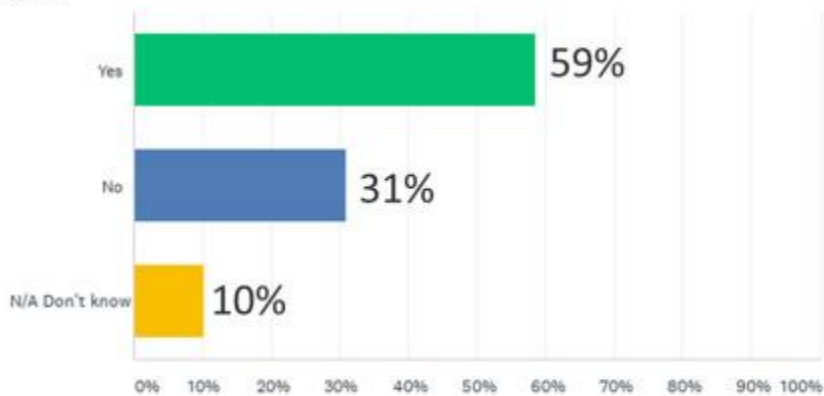
1009

1010

1011   [FIGURE S3]

Q3: What method does your organization typically use for barrier prioritization?
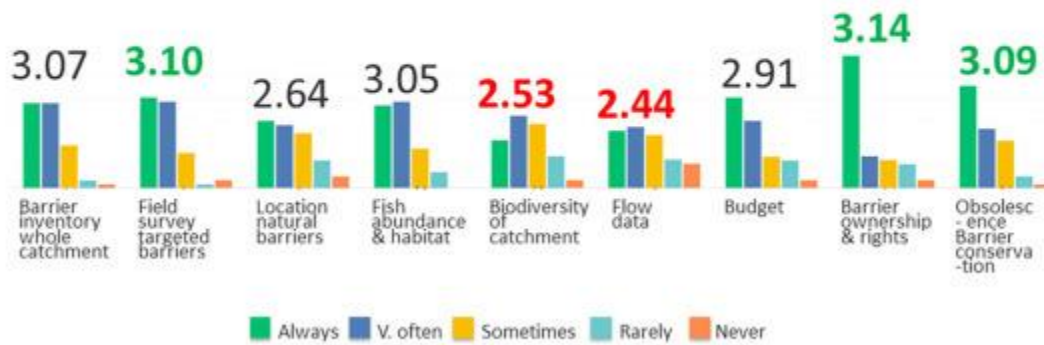
Answered: 58   Skipped: 0
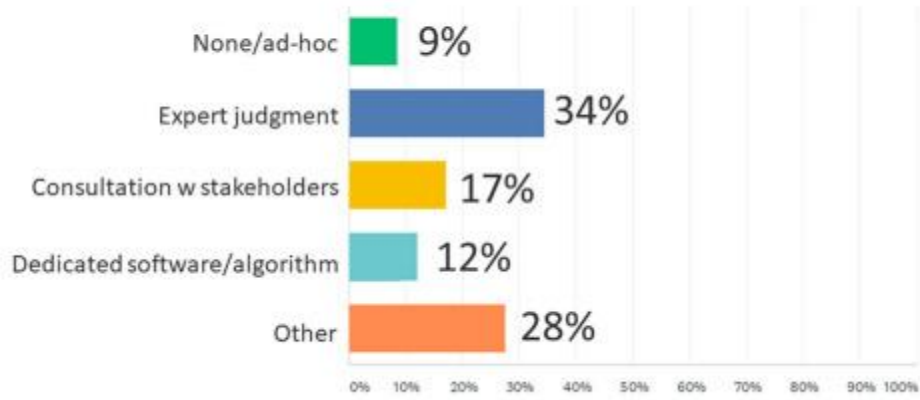
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1013

1014   [FIGURE S4]

Q4: What information/data do you use for barrier prioritization

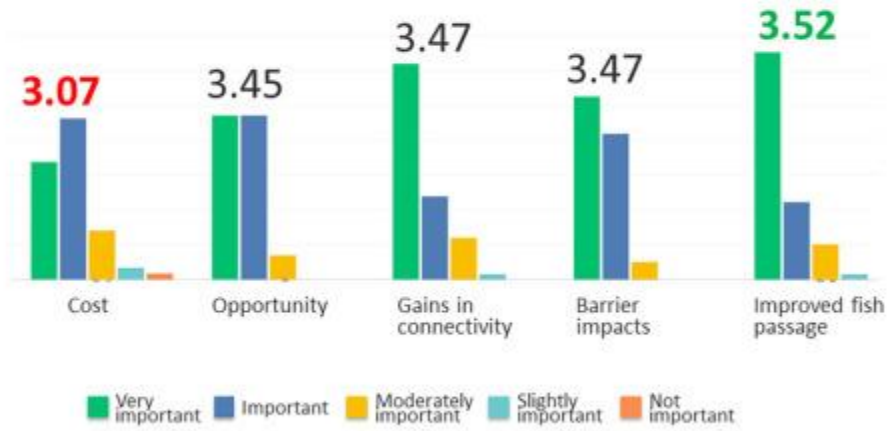Answered: 58   Skipped: 0

1015

1016

1017   [FIGURE S5]

Q5: How important are these criteria for selecting barriers for mitigation in your experience?
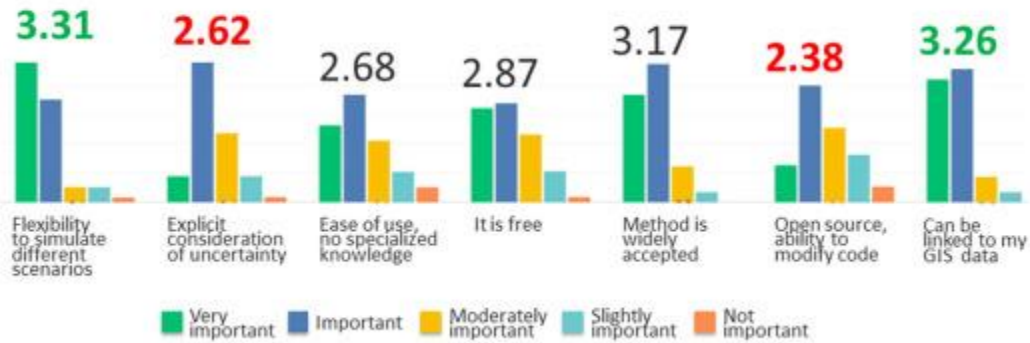
Answered: 58   Skipped: 0

1018

1019

1020   [FIGURE S6]

Q6: What would be the most important features of a barrier prioritization software?

Answered: 58   Skipped: 0

1021

1022