Adaptive management in the context of barriers in European freshwater ecosystems

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Abstract

Many natural habitats have been modified to accommodate for the presence of humans and their needs. Infrastructures – such as hydroelectric dams, weirs, culverts and bridges – are now a common occurrence in streams and rivers across the world. As a result, freshwater ecosystems have been altered extensively, affecting both biological and geomorphological components of the habitats. Many fish species rely on these freshwater ecosystems to complete their lifecycles, and the presence of barriers, has been shown to reduce their ability to migrate and sustain healthy populations. In the long run, barriers may have severe repercussions on population densities and dynamics of aquatic animal species. There is currently an urgent need to address these issues with adequate conservation approaches. Adaptive management provides a relevant approach to managing barriers in freshwater ecosystems as it addresses the uncertainties of dealing with natural systems, and accommodates for future unexpected events, though this approach may not be suitable in all instances. A literature search on this subject yielded virtually no output. Hence, we propose a step-by-step guide for implementing adaptive management, which could be used to manage freshwater barriers.

Keywords: adaptive management, barriers, freshwater ecosystems, stakeholders, conservation

1. Context: barriers in European freshwater ecosystems

In comparison to their terrestrial counterparts, freshwater taxa are on average more imperiled (Dudgeon et al. 2006; Strayer and Dudgeon 2010; Carrizo et al. 2013). Freshwater fish species represent approximately 25% of all living vertebrates, many of which are threatened (IUCN 2016). Given the linear nature of freshwater systems, connectivity may be heavily affected as a result of the presence of in-river barriers (Stanford et al. 1996). Historically, rivers and their surroundings have been used for anthropogenic purposes more than any other habitat, which over centuries, has led to the loss of the original integrity of water courses (Jungwirth 1998; Jager et al. 2001). Today, the majority of large rivers have been modified in one way or another – for the purposes of hydroelectric power plants (Welcomme 1995) or other artificial barriers like dams, weirs, or road crossings (Jungwirth et al. 2000; Nilsson et al. 2005), posing increasing threats to freshwater ecosystems and the mobile biota, particularly fish, that live within them (Arthington et al. 2016).

In Europe, all major rivers, except for the Pechora River in Russia (Studenov et al. 2008), are now fragmented by artificial dams and weirs (Tockner et al. 2009). The high (and increasing) density of river barriers is contributing to the poor habitat quality and loss of biodiversity of freshwater systems in contravention of the European Union’s Water Framework Directive (Acreman and Ferguson 2010; Reyjol et al. 2014). Increasingly, barrier removal is viewed as a necessary management measure to reinstate natural connectivity within and amongst ecosystems (Garcia de Leaniz 2008; Tonra et al. 2015), though we still have little knowledge to make predictions about the biological and geomorphological trajectory of a river system once a barrier has been removed (Pizzuto 2002). Whilst removal projects for large barriers have revealed quick recovery of key biological components (Tonra et al. 2015), the same cannot be said of barriers in small streams as evidence is currently lacking (Tummers et al. 2016a). The presence of small-to-medium sized impoundments (i.e., height below 10m) is extensive in European streams and rivers, providing us with every reason to investigate their effects in order to enhance and focus management efforts.

2. Management of barriers

Many barriers in European rivers originated in the 10^{th} to 19^{th} centuries to operate mills (Downward and Skinner 2005; Nützmann et al. 2011) and a high proportion, often rebuilt or modified multiple times, are now redundant (Downward and Skinner 2005). However, some mill weirs are of historical significance or are being converted for operation as low-head hydroelectric power facilities (Watkin et al. 2012). Since the 1950s, the approach to implement dams for achieving water storage has been to design and operate reservoirs so that they fill with sediments slowly (Palmieri et al. 2001) but some are approaching the end of their operational lives. Currently, there are challenging issues regarding the proper management of barriers, which may be addressed by an adaptive management (AM) approach.

AM stems from the idea that ecosystem management and conservation practice is a dynamic process, and thus should be modified as we gain further knowledge to achieve management objectives (Holling 1978; Lindenmayer and Burgman 2005; Westgate et al. 2013). Such an approach is especially appropriate when dealing with ecological resources, which are dynamic in nature, and hence would provide an appropriate method to manage barriers (for example management of flow characteristics - see Baumgartner et al. 2014; Summers et al. 2015). This dynamic conservation approach has grown greatly since the seminal work of Walters and Hilborn (1976) and Holling (1978), and is now considered fundamental to sustainable practices (Westgate et al. 2013; Williams and Brown 2014). An adaptive approach requires extensive planning, along with an active and systematic effort to gather and document information, as well as the early involvement of stakeholders in the decision-making process (Lindenmayer and Burgman 2005). There are four fundamental elements to AM, as identified by Davis et al. 2001: (1) acknowledging the uncertainties associated with management policies, (2) formulating management policies as testable hypotheses, (3) searching, using and assessing information in order to test hypotheses, and (4) adapting management policies periodically as new information is acquired.

While AM is widely supported in theory (Fabricius and Cundill 2014), few real-world examples have been reported in practice (Keith et al. 2011; Westgate et al. 2013). Most applications test a single management option at a time, and change their approach only when it fails (Duncan and Wintle 2008; Keith et al. 2011). Our initial objective was to use a systematic approach to review the current state of research in adaptive barrier management of freshwater ecosystems. However, an all-time initial search on Web of Science using "(adaptiv*)AND(manage*)AND(freshwater)AND(barrier*)" as the word string yielded only 17 results, 13 of which were eliminated at the title level, and the remaining 4 were eliminated at the abstract level, suggesting that this area of research is highly understudied. We therefore opted to include a broader spectrum of literature, and gather relevant information on AM, in an attempt to apply it directly to barrier management in freshwater ecosystems. While we hoped to provide specific examples to demonstrate how AM has been successfully used in barrier management, the literature on the topic is scarce, although this is partly because some relevant projects that have adopted an AM ethos have not used this term explicitly (*Box* **1**). Instead, we propose a step-by-step guide for how AM could be implemented in the management of freshwater barriers

(*Figure* **1**), along with the potential benefits and challenges that come with using such an approach.

Potential benefits

One of the main advantages of AM is its regular reviews of the effectiveness and progress of the strategies currently in place in the river system being managed. Management objectives should be dynamic in natural systems, such as streams and rivers. Thus, as results are obtained (i.e., research findings), objectives change, and accordingly, so should management strategies (exemplified in *Box* **1**). Modelling tools are essential to understand how environmental factors may impact a system, and to predict the outcomes of various management options (Thom 2000; Bearlin et al. 2002). This approach helps to accommodate for future unexpected events by guiding the development of predictions and hypotheses, which is especially relevant in today's changing world. In barrier management, fish density, diversity, recruitment and spawning provide important metrics to track the efficacy of the management strategies currently in place. Regular revisions of these data will provide valuable information for modelling purposes and help promote future management success of barriers. Modelling is also beneficial to optimize an approach. In many ways, AM resembles a scientific experiment, where hypotheses are tested, and experimentation is carried out, thus rendering the conclusions to be drawn more robust (Linkov et al. 2004).

Potential challenges

A crucial component of AM is its ability to highlight the presence and importance of uncertainties, and to use these uncertainties when formulating and testing hypotheses to render the process more efficient (Davis et al. 2001). In the context of AM, uncertainties arise from changing natural conditions, but also due to economic, social and political variability (Salwasser 1993). Uncertainties must be managed by considering a wide range of adequate, realistic and reversible strategies - essentially replacing the uncertainty of a resource with the certainty of a process (Rodgers 1997). Results should be monitored continuously, and strategies adjusted as further knowledge is gained (Beese et al. 2003; Bunnell et al. 2003). While modeling is used to make predictions that take into account uncertainties, modeling with knowledge gaps (i.e., when all necessary information is not available) may exacerbate this uncertainty. AM is about "learning by doing", and incorporating learnt lessons into future decisions (McDaniels and Gregory 2004). In the context of barriers, managers may use currently available findings (e.g., in the literature or reports) on the potential benefits of barrier removal (or the negative impacts of barrier implementation) for fish and apply this information to a new system, accepting alongside it the uncertainties that come with natural systems and populations.

In the real world, AM is difficult to attain successfully. Stakeholders may have conflicting perspectives despite a conservation objective agreed by all (Lindenmayer and Burgman 2005). In many instances, political and social circumstances make AM a difficult task to fulfill (*Table* **1**). Scientists may not always recognize problems in AM sufficiently, as their solutions are not necessarily socially and politically acceptable (Salwasser 1993). A common caveat to AM is how it manages human motivation, often causing a source of problems in resources management (Ludwig et al. 1993), especially when the main concern should revolve around the resource itself. Stakeholders can sometimes be unwilling to compromise and/or accept *any* change, resulting in serious delays in management efforts, and may even completely stall the process. For example, dams are often constructed to alter flow regimes and generate hydroelectricity (Dynesius and Nilsson 1994), causing substantial impacts on the ecological health of rivers (Bunn and Arthington 2002). Alternatively, old mills and weirs may have historical or cultural value to some, be used for recreational purposes (e.g., boating and fishing) and for supply of drinking water. Stakeholders from both sides must discuss management options, which will likely require compromises. In some cases minor stakeholders who remain completely unwilling to compromise or accept any form of change may simply have to be ignored.

When a resource collapses, all stakeholders typically agree that action must be taken. Nonetheless, complete consensus is almost unattainable, which puts management groups at a standstill. Some challenges are irreconcilable. We must therefore often take action before (scientific) consensus is reached. Unrealistic expectations can sometimes cause us to forget about the problem itself, but this adaptive approach is a trade-off between available data, and the need for immediate resource conservation. For example, the reinstatement of more natural conditions of streams and rivers via barrier removal may be a necessary action to conserve wild fish populations, despite the paucity of data on barrier removal.

Another challenge is that sometimes the problem is thought to be only marginal and so to initiate an AM process would be too costly and lengthy for the benefits. In this case, a potential solution may be to approach the entire river system as one management issue, rather than individual barriers within the system. In catchment management, barriers in small lowland streams are often disregarded and viewed as non-impactful obstacles, though their combined effects are in fact largely underestimated (Tummers et al. 2016a; Birnie-Gauvin et al. *in press*). In many instances, too much emphasis is placed on the measureable economic interests of stakeholders resulting in the underappreciation of conservation problems (often unmeasurable) at hand, thereby slowing the process of experimentation, learning and adaptation. Management then becomes stuck at the modelling step because research is deemed too expensive, which comes at the cost of ecological sustainability.

4. Implementing adaptive management

We propose a guide to implement adaptive management in the real world in *Figure* **1**. Before initiating an AM approach, managers must first determine whether all of the four following components are present: (1) knowledge gaps, (2) prospects for learning and an expected ecological value, (3) opportunities for reconsiderations and alternative options (i.e., if only one option is viable, adaptive management is not an appropriate approach), and (4) sufficient funding. If all four components are present, then one may initiate the AM process, which begins with identifying and involving all relevant stakeholders. Managers must ask themselves three important questions: Are there highly valuable resources at stake? Is the scenario highly politically-involved? Is there a high degree of uncertainty revolving around this issue? If “yes” is answered to any of these questions, it is highly recommended that managers seek the help of independent peer-reviewers to help the decision-making process. The following step is one of the most critical steps in AM: setting clear objectives, which are agreed upon by all stakeholders. Without agreement, the process cannot move forward, sometimes at the cost of ecological resilience. Independent peer-reviewers may be helpful, but if the opinions of stakeholders are irreconcilable, then an alternate management approach must be investigated. Managers must then identify measurable indicators (of the chosen management actions), which must again be agreed upon. The modeling process subsequently begins, which helps the development of hypotheses and predictions, and vice versa. Following modeling, large-scale experimentation is carried out, where the outcomes are evaluated. If the outcomes are not satisfactory, then more modeling and hypothesis-testing may be needed. If the outcomes are deemed satisfactory by stakeholders, the agreed upon management actions may be implemented and evaluated repeatedly at regular intervals. Discussions, reflections and adaptations to the management approach should be undertaken continuously. Every step of this process should be documented adequately.

5. Conclusion and an outlook to the future

In many cases, “we know too little about how threats operate at large scales to be able to prevent or mitigate them” (Abell 2002). Adaptive management attempts to deal with the uncertainties that come with “knowing too little”. Nonetheless, there are instances in which adaptive management is simply not an acceptable option (*Table* **2**), a fact which cannot be understated - adaptive management is by no means the answer to every conservation issue. There exist several guidelines and prerequisites that must be met before one can set out to implement an adaptive management approach (*Figure* **1**). Under certain circumstances, it may be valuable to combine an adaptive management approach with other approaches to developed tools which can be applied at a wider scale (e.g., Fuzzy Cognitive Mapping, Özesmi et al. 2004). In cases when adaptive management can be used, it is important that the process and outcomes - for both failures and successes - be documented (either as a report or peer-reviewed article) so that others can benefit from it. It may also be beneficial to managers if a formal framework on how to implement adaptive management is available.

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References

Abell, R. (2002). Conservation biology for the biodiversity crisis: a freshwater follow-up. *Conservation Biology* **16**: 1435-1437.

Acreman, M.C., Ferguson, A.J.D. (2010). Environmental flows and the European Water Framework Directive. *Freshwater Biology* **55**: 32-48.

Arthington, A.H., Dulvy, N.K., Gladstone, W., Winfield, I.J. (2016). Fish conservation in freshwater and marine realms: status, threats and management. *Aquatic Conservation: Marine and Freshwater Ecosystems* **26**: 838–857.

Baumgartner, L.J., Conallin, J., Wooden, I., Campbell, B., Gee, R., Robinson, W.A., Mallen-Cooper, M. (2014). Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semi-arid riverine systems. *Fish and Fisheries* **15**: 410-427.

Bearlin, A.R., Schreiber, E.S.G., Nicol, S.J., Starfield, A.M., Todd, C.R. (2002). Identifying the weakest link: simulating adaptive management of the reintroduction of a threatened fish. *Canadian Journal of Fisheries and Aquatic Sciences* **59**: 1709-1716.

Beese, W. J., Dunsworth, B. G., Zielke, K., Bancroft, B. (2003). Maintaining attributes of old-growth forests in coastal BC through variable retention. *The Forestry Chronicle* **79**: 570-578.

Birnie-Gauvin, K., Aarestrup, K., Riis, T.M.O., Jepsen, N., Koed, A. (in press). Shining the 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*. doi: 10.1002/aqc.2795

Bracken, F.S.A., Lucas, M.C. (2013). Potential impacts of small-scale hydroelectric power generation on downstream moving lampreys. *River Research and Applications* **29**: 1073-1081.

Bracken, F.S.A., Hoelzel, A.R., Hume, J.B., Lucas, M.C. (2015). Contrasting population genetic structure among freshwater-resident and anadromous lampreys: the role of demographic history, differential dispersal, and anthropogenic barriers to movement. *Molecular Ecology* **24**: 1188-1204.

Bunn, S.E., Arthington, A.H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **20**: 492-507.

Bunnell, F.L., Dunsworth, B.G. (2004). Making adaptive management for biodiversity work the example of Weyerhaeuser in coastal British Columbia. *The Forestry Chronicle* **80**: 37-43.

Carrizo, S.F., Smith, K.G., Darwall, W.R.T. (2013). Progress towards a global assessment of the status of freshwater fishes (Pisces) for the IUCN Red List: application to conservation programmes in zoos and aquariums. *International Zoo Yearbook* **47**: 46-64.

Davis, M.B., Shaw, R.G. (2001). Range shifts and adaptive responses to quaternary climate change. *Science* **292**: 673-679.

Downward, S., Skinner, K. (2005). Working rivers: the geomorphological legacy of English freshwater mills. *Area* **37**: 138-147.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C., Sullivan, C.A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* **81**: 163-182.

Duncan, D.H., Wintle, B.A. (2008). Towards adaptive management of native vegetation in regional landscapes. In: Pettit, C., Bishop, I., Cartwright, W., Duncan, D., Lowell, K., Pullar, D. eds. Landscape Analysis and Visualisation. Spatial models for Natural Resource Management and Planning. Berlin, Springer-Verlag GmbH, pp. 159-182.

Dynesius, M., Nilsson, C. (1994). Fragmentation and flow regulation of river systems in the northern third of the world. *Science* **5186**: 753-762.

Fabricius, C., Cundill, G. (2014). Learning in adaptive management: insights from published practice. *Ecology and Society* **19**: 29-36.

Foulds, W.L., Lucas, M.C. (2013). Extreme inefficiency of two conventional technical fishways used by European river lamprey (*Lampetra fluviatilis*). *Ecological Engineering* **58**: 423-433.

Garcia de Leaniz, C. (2008). Weir removal in salmonid streams: implications, challenges and practicalities. *Hydrobiologia* **609**: 83-96.

Holling, C.S. (1978). Adaptive Environmental Management and Assessment. Chichester, John Wiley and Sons.

IUCN (2016). IUCN Red List: An overview of the IUCN red list. International Union for the Conservation of Nature and Natural Resources.

Jager, H.I., Chandler, J.A., Lepla, K.B., Winkle, W.V. (2001). A theoretical study of river fragmentation by dams and its effects on white sturgeon populations. *Environmental Biology of Fishes* **60**: 347-361.

Jang, M.--H., Lucas, M.C. (2005). Reproductive ecology of the river lamprey. *Journal of Fish Biology* **66**: 499-512.

Jungwirth, M. (1998). River continuum and fish migration – Going beyond the longitudinal river corridor in understanding ecological integrity. In: Jungwirth, M., Schmutz, M. S., Weiss, S.

(eds.). Fish migration and fish bypasses. Fishing News Books. Blackwell Science Ltd., Oxford, pp. 127-145.

Jungwirth, M., Muhar, S., Schmutz, S. (2000). Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. *Hydrobiologia* **422**: 85-97.

Keith, D.A., Martin, T.G., McDonald-Madden, E., Walters, C. (2011). Uncertainty and adaptive management for biodiversity conservation. *Biological Conservation* **144**: 1175-1178.

Lindenmayer, D.H., Burgman, M.A. (2005). Practical Conservation Biology. Collingwood, CSIRO. 610 pp.

Linkov, T.S., Varghese, A., Jamil, S., Seager, T.P., Kiker, G., Bridges, T. (2004). Multi-criteria decision analysis: framework for applications in remedial planning for contaminated sites. In: Linkov, I., Ramadan, A. (eds.). Comparative Risk Assessment and Environmental Decision Making. Amsterdam, Kluwer, pp. 15-54.

Lucas, M.C., Bubb, D.J., Jang, M.-H., Ha, K., Masters, J.E.G. (2009). Availability of and access to critical habitats in regulated rivers: iImpacts of low-head barriers on threatened lampreys. *Freshwater Biology* **54**: 621-634.

Ludwig, D. (1993). Environmental sustainability: magic, science, and religion in natural resource management. *Ecological Applications* **3**: 555-558.

McDaniels, T.L., Gregory, R. (2004). Learning as an objective within a structural risk management decision process. *Environmental Science and Technology* **38**: 1921-1926.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science* **308**: 405-408.

Nunn, A.D., Harvey, J.P., Noble, R.A.A., Cowx, I.G., (2008). Condition assessment of lamprey populations in the Yorkshire Ouse catchment, north-east England, and the potential influence of physical migration barriers. *Aquatic Conservation: Marine and Freshwater Ecosystems* **18**: 175-189.

Nützmann, G., Wolter, C., Venohr, M.,. Pusch, P. (2011). Historical patterns of anthropogenic impacts on freshwaters in the Berlin-Brandenburg region. *Die Erde* **142**: 41-64.

Özesmi, U., Özesmi, S. L. (2004). Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling* **176**: 43-64.

Ovidio, M., Philippart, J.C. (2002). The impact of small physical obstacles on upstream movements of six species of fish. *Hydrobiologia* **483**: 55-69.

Palmieri, A., Shah, F., Dinar, A. (2001). Economics of reservoir sedimentation and sustainable management of dams. *Journal of Environmental Management* **61**: 149-163.

Pizzuto, J. (2002). Effects of dam removal on river form and process: Although many well-established concepts of fluvial geomorphology are relevant for evaluating the effects of dam removal, geomorphologists remain unable to forecast stream channel changes caused by the removal of specific dams. *BioScience* **52**: 683-691.

Reyjol, Y., Argillier, C., Bonne, W., Borja, A., Buijse, A.D., Cardoso, A.C., Prat, N. (2014). Assessing the ecological status in the context of the European Water Framework Directive: Where do we go now? *Science of the Total Environment* **497**: 332-344.

Rodgers, W.H. (1997). Environmental Law, second edition. West Publishing, St. Paul, Minnesota, USA.

Royal Haskoning (2010). Yorkshire Derwent Restoration Plan. http://www.therrc.co.uk/DesignatedRivers/Yorks_Derwent_Restoration_Plan.pdf

Salwasser, H. (1993). Sustainability needs more than better science. *Ecological Applications* **3**: 587-589.

Saunders, D.A., Hobbs, R.J., Margules, C.R. (1991). Biological consequences of ecosystem fragmentation: A review. *Conservation Biology* **5**: 18-32.

Silva, S., Lowry, M., Macaya, C., Byatt, B., Lucas, M.C. (2017). Can navigation locks be used to help migratory fishes with poor swimming performance pass tidal barrages? A test with lampreys. *Ecological Engineering* **102**: 291-302.

Stanford, J. A., Ward, J. V., Liss, W. J., Frissell, C. A., Williams, R. N., Lichatowich, J. A., Coutant, C. C. (1996). A general protocol for restoration of regulated rivers. *River Research and Applications* **12**: 391-413.

Strayer, D.L., Dudgeon, D. (2010). Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society* **29**: 344-358.

Studenov, I., Antonova, V., Chuksina, N., Titov, S. (2008). Atlantic salmon of the Pechora River. SevPINRO, Arkhangelsk, pp 52.

Summers, M.F., Holman, I.P., Grabowski, R.C. (2015). Adaptive management of river flows in Europe: A transferable framework for implementation. *Journal of Hydrology* **531**: 696-705.

Thom, R.H. (2000). Adaptive management of coastal ecosystem restoration projects. *Ecological Engineering* **15**: 365-372.

Tockner, K., Uehlinger, U., Robinson, C.T. (eds.) (2009). Rivers of Europe. Academic Press, Oxford, UK.

Tonra, C.M., Sager-Fradkin, K., Morley, S.A., Duda, J.J., Marra, P.P. (2015). The rapid return of marine-derived nutrients to a freshwater food web following dam removal. *Biological Conservation* **192**: 130-134.

Travade, F., Larinier, M. (1992). Downstream migration: problems and facilities. *Bulletin Francais de la Peche et de la Pisciculture* **364**: 181-207.

Tummers, J.S., Hudson, S., Lucas, M.C. (2016a). Evaluating the effectiveness of restoring longitudinal connectivity for stream fish communities: towards a more holistic approach. *Science of the Total Environment* **569-570**: 850-860.

Tummers, J.S., Winter, E., Silva, S., O'Brien, P., Jang, M.-H., Lucas, M.C. (2016b). Evaluating the effectiveness of a Larinier super active baffle fish pass for European river lamprey *Lampetra fluviatilis* before and after modification with wall-mounted studded tiles. *Ecological Engineering* **91**: 183-194.

Vowles, A.S., Don, A.M., Karageorgopoulos, P., Kemp, P.S. (2017). Passage of European eel and river lamprey at a model weir provisioned with studded tiles. *Journal of Ecohydraulics* **2**: DOI 10.1080/24705357.2017.1310001

Walters, C.J., Holling, C.S. (1990). Large-scale management experiments and learning by doing. *Ecology* **71**: 2060-2068.

Walters, C., Hillborn, R. (1976). Adaptive control of fishing systems. *Journal of the Fisheries Research Board of Canada* **33**: 145-159.

Watkin, L.J., Kemp, P.S., Williams, I.D., Harwood, I.A. (2012). Managing sustainable development conflicts: the impact of stakeholders in small-scale hydropower schemes. *Environmental Management* **49**: 1208-1223.

Welcomme, R.L. (1995). Relationships between fisheries and integrity of river systems. *Regulated Rivers: Research and Management* **11**: 121-136.

Westgate, M.J., Likens, G.E., Lindenmayer, D.B. (2013). Adaptive management of biological systems: a review. *Biological Conservation* **158**: 128-139.

Williams, B.K., Brown, E.D. (2014). Adaptive management: from more talk to real action. *Environmental Management* **53**: 465-479.

Table **1**. Stakeholders and their incentive for barrier management.

Stakeholder	**Underlying incentive**
Hydroelectric dam owner	Economic value, provision of energy
Residents of local municipality	Flood risk (economic impact), cultural heritage, recreation (boating, fishing, wildlife)
Environmental protection agencies	Flow gauging, flood risk
Water companies	Economic value, water abstraction for drinking water
Farmers of adjacent land	Economic value, water abstraction for crops, flood risk adjacent to river
Boat navigation	Channel depth management, economic value
Highways / rail authority	Economic value, transport where barrier issue is linked to road/rail transport (culvert, bridge infrastructure)
Fish farmers	Economic value, stocking
Recreational fishing	Economic value, intrinsic values
Commercial fishing	Economic value, food provision
Conservation bodies	Maintaining biodiversity, environmental and population sustainability

Table **2**. Limitations of the adaptive management approach.

Instances when NOT to use adaptive management
To delay a process.
When there are no knowledge gaps.
When no clear objectives have been set.
When funding is a problem.
When opportunities for improvement lack.
When later reconsiderations are not an option.
When alternatives are limited.
When mistakes are irreversible.
When no measurable indicators are available.
Irreconcilable stakeholders

Box **1**. Adaptive management of river barriers in action - a case study

The Yorkshire Derwent, northeast England is a tributary of the Humber, the UK's largest drainage. The Derwent catchment is mostly rural and has good water quality, suitable for potable supply after treatment. The catchment runs off the North Yorkshire Moors but the last 75 km of river falls only 20 m (mostly at six river barriers), creating a large managed floodplain. The downstream-most 35km of this comprises herb-rich damp meadows. From km 68 to the confluence with the Humber, the river was designated a national Site of Special Scientific Interest (SSSI) in 1975 and an EU Special Area of Conservation (SAC) in 2005. Adjacent wetlands form an EU Special Protection Area (SPA) for wetland birds and a RAMSAR wetland site. *Ranunculion fluitantis / Callitrichio-Batrachion* habitat and river lamprey *Lampetra fluviatilis* were primary reasons for selection of the lower Derwent as an SAC. However, since 2003, Natural England (NE) determined the Derwent SAC to be in unfavourable condition for these features. Key pressures were identified as siltation, and in-river barriers to fish movement. Additional management issues relating to River Derwent barriers are flood risk management (towns along the lower Derwent have flooded multiple times in recent decades); potable water supply (the lower two barriers stabilise water levels upstream for abstraction to 5 million people); new low-head hydroelectricity (the Environment Agency [EA] is required to support renewable power development alongside its environmental protection duties); flow-gauging (EA gauges river flow from several weirs) and navigation (on the lower 35 km of river, including to and from the Humber, via Barmby tidal barrage, the downstream-most barrier, managed by EA). In 2003 the EA and NE sought to develop a long-term ecological restoration plan for the river (River Derwent Restoration Project, RDRP), in an adaptive framework and consulted with a wide range of stakeholders, identifying objectives and information needs.

To provide information for the RDRP and more widely, lamprey research on the Derwent has included determining their abundance and distribution (Jang and Lucas 2005; Nunn et al. 2008; Lucas et al. 2009); the distribution and use of lamprey habitats (Jang and Lucas 2005); the effect of habitat fragmentation on lamprey population genetics (Bracken et al. 2015); migration and passability of different barriers and the utility of various fishway designs (Lucas et al. 2009; Foulds and Lucas 2013; Tummers et al. 2016b; Silva et al. 2017); and hydroelectricity impacts on lampreys (Bracken and Lucas 2013). The River Derwent Restoration Plan (Royal Haskoning 2010) evaluated multiple options for solving in-river barrier impacts, site by site, including full barrier removal, barrier height reduction and provision of fishways. These options were appraised in concert with opportunities for reducing flood risk, managing key infrastructure (e.g. water abstraction), supporting hydroelectricity development, and the economic costs and benefits. This continues to be an ongoing adaptive process. For example, in 2010 EA decided not to remove its redundant flow-gauging weir at rkm 40, but to allow commercial hydroelectric development there and build a Larinier superactive baffle fishway, in the expectation that this would be usable by river lamprey. Research has since shown the Larinier design to be ineffective for lamprey upstream passage (Tummers et al. 2016b) and alternative passage solutions are being researched (Vowles et al. 2017). Modelling of weir height reductions at several other sites has been done and engineering options and costs for height reduction are actively being pursued. Since 2006, at Barmby tidal barrage, operations and automated controls have been altered, tested and improved to enhance fish passage, particularly through the use of the navigation lock in 'fishway mode' (Silva et al. 2017). Although this is intended for lamprey migration it can likely benefit eels, flatfish and Atlantic salmon *Salmo salar*, which are starting to recolonize the river after an absence of many decades due mostly to pollution of the Humber estuary.

Figure **1**. Proposed step-by-step guide to implement an adaptive approach in barrier management.