RECOMMENDATIONS FOR A "COARSE-RESOLUTION RAPID-ASSESSMENT" METHODOLOGY TO ASSESS BARRIERS TO FISH MIGRATION, AND ASSOCIATED PRIORITIZATION TOOLS.

FINAL REPORT

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1. SUMMARY

The high density of structures, such as dams, weirs, and culverts, throughout the watercourses of the British Isles reflect a historic legacy of extensive river development. Anthropogenic structures can negatively affect ecological processes, reduce habitat connectivity, and significantly impact the population viability of a diverse range of aquatic biota. Fish stocks are particularly affected as movements between essential habitats, e.g. for feeding or spawning, are impeded. The European Union Water Framework Directive requires that Member States achieve "good" surface water status for all surface water bodies, and "good" ecological potential for those water bodies that are heavily modified. There is a requirement to identify the impact of structural barriers on aquatic ecosystems to ensure that the Member States that form the British Isles are able to effectively classify surface water bodies in line with the requirements of the Water Framework Directive, and to implement strategies of mitigation, where necessary, to meet the objectives set.

The objective of this report is to critically evaluate methodologies that are currently employed to assess the "porosity" of structural barriers to fish movements; to classify status of water bodies; and to prioritize restoration efforts. The report provides recommendations for the adoption of a "coarse-resolution rapid assessment" methodology to assess the porosity of barriers to fish migration for use within the context of the British Isles.

The majority of current methodologies for the assessment of structural impediments to fish movement have been developed in the United States. The methodologies are biased towards consideration of culverts, and are dependent on fish passage criteria that are based primarily on the swimming capabilities of upstream migrating adult salmonids. Gaps in understanding relate to non-salmonid species, downstream migrating life-stages, and consideration of behaviour. A protocol for barrier porosity assessment suitable for application within the British Isles is presented as part of this report. It is important that this protocol be iteratively developed as understanding of the requirements for fish

passage of multiple species and life-stages, during both upstream and downstream migration, is improved. More research is required to define fish passage criteria for multiple species and life-stage based on both behavioural and physical components of performance.

The proposed methodology is based on a "coarse-resolution" assessment (Level A) of barrier porosity based on quantitative and subjective data collected in the field. A central inventory must be constructed to maintain barrier data collected. At the interface of the assessment protocol and data maintenance, a process of data interrogation is required to assign values of barrier porosity. This will involve access to, and acquisition of, other relevant data available in the public domain. It is essential that a mechanism for feed-back exists whereby further fine-resolution assessments (Level B or C) of specific barriers are conducted if necessary. It is important that the development of the assessment protocol occurs in parallel with the construction of an appropriate database system. The database must be compatible with other national systems and it is recommended that it is supported by GIS based geospatial maps of catchment-scale fish migration barrier networks.

Despite the availability of several methodologies to assess barrier porosity, and recommendations for the construction of inventories to maintain the information collected, the development of tools that facilitate the classification of water bodies and prioritization of restoration efforts remain in their infancy. It is recommended that classification system employs subjective analysis based on cumulative values of fish migration barrier network porosity, taking into account other socio-political factors. Examples of how this may be achieved are provided but ultimately remain the responsibility of the policy makers. Current prioritization tools are biased towards simplistic "scoring and ranking" systems that, in many cases, provide significantly suboptimal solutions because individual barriers are considered independent of the network. It is proposed that prioritization mechanisms are developed that employ optimization and heuristic network modelling approaches. It is recommended that appropriate methodologies that are currently available and widely used in other areas (e.g., transport system planning) be adapted to prioritize most appropriate restoration actions in relation to barrier removal or repair. The development of methodologies for assessment, data maintenance, and prioritization must occur in parallel in a cohesive and integrated manner. It is recommended that the development of the methodologies involve input from a consortium of all stakeholders, including academic institutions, so that appropriate sources of funding for future phases of the project may be identified. The development of links, via an appropriate international network, with other agencies (e.g. in North America) that are currently pursuing similar projects, will likely prove beneficial in terms of gaining added value via knowledge transfer, and thus reduce the potential for duplication of effort.

2. INTRODUCTION

In-river structures, such as dams, weirs and culverts, are a major cause of habitat fragmentation in fluvial ecosystems. These structures can partially or fully impede the movement of fish between essential habitats and negatively impact population status (Lucas & Baras, 2001). The negative impact of various barrier types on diadromous and resident species of fish can be highly variable, ranging from short delays to complete obstruction, and are dependent on nature of the barrier, river hydrology, and species (e.g., timing of migration and swimming capabilities) (Northcote, 1998). Complete barriers prevent fish accessing essential habitat for rearing and spawning, and can reduce distribution so that dwindling populations becoming increasingly isolated and suffer a greater risk of extinction. Alternatively, partial or temporal barriers (e.g. culverts) can block the movements of a proportion of the population that are weaker swimmers or younger life-stages, or reduce access at certain times (e.g. high or low flows). Therefore, complete and partial or temporal impediments can impact populations by increasing mortality and predation and decreasing egg production (O'Hanley and Tomberlin, 2005).

The European Union Water Framework Directive (WFD) requires that Member States aim to achieve "Good Ecological Status", or "Good Ecological Potential" in the case of heavily modified water bodies, by 2015. It is recognized that one of the most effective mechanisms to achieve this is to mitigate for the impact of barriers on ecological processes such as those described by the River Continuum Concept (Vannote *et al.*, 1980). Based on studies conducted in North America that have evaluated the relative benefits of different types of habitat rehabilitation techniques, the removal or mitigation of barriers that block fish migrations have led to some of the largest increases in fish production (Roni *et al.*, 2002). That is, mitigation or removal of barriers to fish movement provides "the biggest bang for the buck" in relation to restoring ecological connectivity. For example, Scully *et al.* (1990) observed that 70% of increases in fish production in rehabilitated Idaho streams were due to barrier removal versus instream and other rehabilitation techniques. Furthermore, the benefits of removing barriers can be realised relatively quickly, as increased fish abundance / productivity have been observed within one year of barrier removal (Roni *et al.*, 2002). To enable water resource managers and regulators meet the obligations of the WFD, appropriate methodologies are required that will enable the assessment of barrier porosity to fish movement; the development of an inventory of barriers; and the prioritization of those for correction based on the magnitude of negative impact relative to positive gains attained by mitigation.

To quantify the permeability of structures to fish movement, fish passage criteria for multiple species must be developed. Once fish passage criteria are defined, the identification of complete physical barriers to migration can be relatively straight-forward. However, partial barriers may not physically obstruct fish movement, but create an impediment under specific flow conditions when depths are insufficient or velocities exceed swimming capabilities of the target species. Current understanding, however, is biased towards swimming capabilities of upstream migrating adult salmonids, while little is known of the constraints of non-salmonids (Lucas and Frear, 1997). There is a need to consider downstream migrating life-stages, and the movements of multiple species, especially those that now receive legislative protection, such as eel (*Anguilla anguilla*) and the three species of lamprey (*Lampetra fluviatilis, L. planeri, and Petromyzon marinus*) found in the British Isles. Eels are due to be listed under Appendix II of CITES in March 2009, and there is a requirement to develop "Eel Management Plans" in 2008 aimed at achieving 40% adult eel biomass migration from UK waters. All three species of lamprey are included in Annex II of the European Habitats and Species Directive 92/43/EEC.

The ability of several species of fish to negotiate impediments to movement is influenced by the behaviour they exhibit on encountering physical structure. For example, downstream migrating salmonids (commonly referred to as smolts) are known to exhibit avoidance to abrupt velocity gradients (Kemp *et al.*, 2005a; Kemp *et al.*, 2006), such as at weirs, and overhead cover associated with culverts (Kemp *et al.*, 2005b), that can delay migration and potentially result in increased predation risk and energetic expense. It is important to consider both swimming capabilities and behaviour of multiple species when defining criteria to describe the permeability of barriers to fish migration.

Fish passage criteria, based primarily on knowledge of swimming capabilities, for some species and life-stages are currently available. These may be used to evaluate the porosity of in-river structures to fish movement. Further, telemetry techniques (e.g., Passive Integrated Transponder [PIT] and Radio telemetry) may be used either to validate evaluations, or to provide empirical data on fish passage for individual or multiple structures. Unfortunately, the abundance of anthropogenic obstacles to fish migration, an artifact of a long historic legacy of river development in the British Isles, makes the use of empirical techniques for national-scale evaluation unfeasible. Instead, a “coarse-resolution rapid-assessment” methodology is needed to effectively define barrier porosity on which an inventory can be constructed to facilitate prioritization for the mitigation or removal of barriers in a cost effective manner. There is a related requirement to use the information maintained in the database to construct a national map of the fish migration barrier network. Based on cumulative barrier porosity, subjective threshold criteria should be developed to enable catchments to be classified as “high”, “good”, “moderate”, “poor”, and “bad” as required by the WFD.

This report provides recommendations of how a methodology appropriate for the British Isles can be developed based on adopting and modifying expert systems used elsewhere (United States and Europe) to assess the porosity of structural barriers to fish migration; develop an inventory of barriers; and prioritize barriers for removal or mitigation. It is not the intention of this report to develop guidelines for the design of fish passage facilities or screening structures as comprehensive manuals are widely available (see Environment Agency Fish Pass manual). The project provides an opportunity to develop a world leading "state-of-the-art" tool to categorize, map, and prioritize the mitigation or removal of barriers that impede fish movement, and thus enhance “Ecological Status” and “Potential” to meet the obligations defined by the WFD.

3. OBJECTIVES

The report aims to meet the following objectives:

- Review literature and critically evaluate existing methodologies used elsewhere to assess barrier porosity to fish migration; develop inventories of barriers; and prioritize barriers for removal or mitigation.
- Provide recommendations of how existing methodologies may be adopted and / or adapted for use in the British Isles.
- Provide recommendations for illustration of fish migration barrier network and how threshold values may be used to classify rivers on the basis of barriers to fish migration.
- Identify data requirements for the development of fish passage criteria and associated caveats to these.
- Develop a guidance manual and field assessment forms to facilitate evaluation of the porosity of fish migration barriers.

4. DEFINITION OF BARRIER POROSITY

It is important to define what is meant by the phrase “barrier porosity” when considering the movements of fish, as other terms are used synonomously throughout the literature. For the purpose of this report, the terms fish passage efficiency, barrier passability, or barrier porosity will be considered to be the same. There are, however, a range of definitions for these terms. To some, barriers are either passable or not (binary measure), and where the passability is unknown, a third score of “undetermined” may be applied. Often this coarse-resolution assessment is based on the presence or absence of populations upstream of the barrier. The reality is much more complicated. Barriers porosity may be temporally variable and a value of passability may be the number of days during the period of the target species migration during which fish are able to pass the barrier (e.g. culverts may not be passable during periods of high or low flows when velocities are either too great, or depths insufficient, to enable fish to move upstream). Barrier porosity may also vary with species, life-stage, body length, and temperature in response to variation in swimming performance. Measures of fish passage efficiency may also vary dependent on whether the perspective is of that of an individual or population. O'Hanley and Tomberlin (2005) define barrier passability to be the fractional rate (within the range 0 – 1) at which fish are able to pass through a barrier while migrating upstream (note bias to considerations of upstream migration only). If we consider passability at the individual level, this may be reflected as the success rate relative to the number of attempts to negotiate the barrier before successfully doing so. At the population level, fish passage efficiency may be defined as the number of successful passes as a proportion of the number of attempts, or the proportion of the population that eventually pass the structure (e.g., Haro *et al.*, 2004). Conversely, lack of attempts to pass a structure should not necessarily be deemed to be an inability or failure to pass, as fish may not be sufficiently motivated to do so, e.g., because they have selected to stop migrating and utilize habitat downstream of the impediment (Ovidio *et al.*, 2007).

The time taken to pass a barrier is an important consideration when assessing porosity. Delayed migration can have significant impacts on individual energetic costs, predation risk, and timing of arrival at the final destination, potentially disrupting adapted physiological transition (e.g., smoltification and estuarine arrival for juvenile salmonids). Therefore, passability may incorporate measures of delay associated with the barrier relative to time taken to pass an equivalent distance of unimpeded river. In instances where the structural impediment is provisioned with a facility for fish passage, passability might also consider the efficiency with which fish are attracted to, or guided towards (in cases where screening or other diversion structures are used) the fish pass entrance. The measure of barrier porosity may vary considerably dependent on whether the proportion of fish that approach the barrier is considered relative to the proportion of fish that enter the fish pass.

In many situations where information is needed to assess the impact of complex physical and hydraulic impediments to fish passage, or the cumulative effect of multiple barriers, several measures of porosity may prove useful (e.g., delay, guidance efficiency, and temporal fish passage efficiency as a proportion of the number of attempts to pass). Indeed, it is recommended that in cases where the cumulative impacts of hydroelectric schemes must be assessed, fine-resolution techniques employing telemetry will provide the most appropriate methodology. To facilitate the prioritization of small barriers for mitigation or removal at a national level, however, a "coarse-resolution" methodology will provide a pragmatic solution, at least at the first iterative phase of assessment.

For the purpose of the course resolution assessment methodology, it is recommended that barrier porosity is defined as:

The proportion of fish that encounter an impediment and then successfully pass it (during either an upstream or downstream migration) without undue delay (i.e. the probability of reaching the final destination, e.g. spawning or feeding grounds, is not comprised due to increased energetic expense or predation risk).

5. IDENTIFICATION AND CRITICAL REVIEW OF METHODOLOGIES FOR ASSESSING THE POROSITY OF BARRIERS TO FISH MIGRATION; MAINTENANCE OF DATA; AND PRIORITIZATION OF BARRIERS FOR REMOVAL OR MITIGATION

This section details available methodologies used to assess porosity of barriers to fish in an effort to develop inventories that will facilitate prioritization for removal or mitigation.

5.1. United States

There are several methodologies that have independently been developed by the US State Fish and Wildlife Agencies for the purpose of documenting and prioritizing barrier to fish migration. The most sophisticated of these were developed for salmonid fisheries along the Western seaboard and hence tend to be "salmonid centric", i.e. do not consider multiple species. Fish passage criteria on which measures of porosity are based also tend to be biased towards measures of fish swimming capability and often ignore behavioural components. Nevertheless, the methodologies have been extensively trialled and likely offer the most promising template for a British model.

The Washington Department of Fish and Wildlife (WDFW) developed the Salmonid Screening, Habitat Enhancement, and Restoration (SSHEAR) fish passage barrier and surface water diversion screening and prioritization tool (WDFW, 2000). The tool enables identification and prioritization of anthropogenic features such as culverts, dams, and fishways that impede fish. As assessments of fish passes or fishways are beyond the scope of this report, the methodology associated with their evaluation will not be considered further. The methodology can be divided into three components. First, the potential for fish to pass the barrier is assessed. Second, an inventory of all potential barriers is constructed. Third, the inventory is used as a tool to help develop strategies that prioritize barriers for potential removal or mitigation. A manual providing guidelines for the methodology enables assessment of river infrastructure. Field assessment forms are completed and forwarded to the central data repository held by the WDFW, where trained staff evaluate the structure and enter information on barrier porosity into the central database. The general assessment protocol (Fig. 1) is flexible and depends on the objectives set. In some cases the objective may be to develop an inventory of a specific type of barrier, whereas others may aim to develop a prioritization strategy taking into consideration multiple barrier types (WDFW, 2000).

Based on the objectives set, the approach adopted is defined before conducting barrier surveys. Inventories may be developed based on either a road- or stream-based approach (WDFW, 2000). A road based approach usually involves driving the roads within the prescribed boundaries and then assessing structures, predominantly culverts, at sites where roads and stream intersect.

The stream-based approach requires that all anthropogenic features are recorded and evaluated, most often by walking the various streams and rivers and conducting an inventory of structures encountered. Both approaches can be conducted at either a catchment or jurisdictional scale, during which all streams and road crossings that are designated as “fish bearing” are respectively walked or driven within the catchment or area of ownership (e.g., county or state highways if road-based). It is interesting to note that the resolution of the survey approach adopted ranges from rapid coarse evaluations to full physical surveys of stream reaches that provide the best estimate of habitat availability and the highest levels of certainty that all anthropogenic features have been identified and located. The level of resolution required depends on pragmatic considerations of the trade-off between expediency and accuracy (WDFW, 2000).

At each structure, the first step is to identify location (e.g. by using GPS technology) and ownership. A multitude of attributes are recorded which include the name of group / agency conducting the survey; the site location (e.g., latitude and longitude, road name, mile post, river mile, county, WDFW region, Washington State department of Transport District) and ownership; structure type; name of stream and main river that the stream is tributary of; indicator of fish use in stream (designated as yes, no, or unknown) and potential species.

The next stage is to determine the potential of the stream to maintain viable populations of fish. This is based on the following state specific criteria as defined by WDFW (2000):

- Water courses having average ordinary high-water widths in excess of 0.6 m in Western Washington and 0.9 m in Eastern Washington provided the stream gradient is less than 20%.
- Water courses identified in WDFW’s Priority Habitats and Species database as fish bearing.
- Water courses listed as Type 1, 2, 3, or 4 on the Department of Natural Resources Water Type Maps.

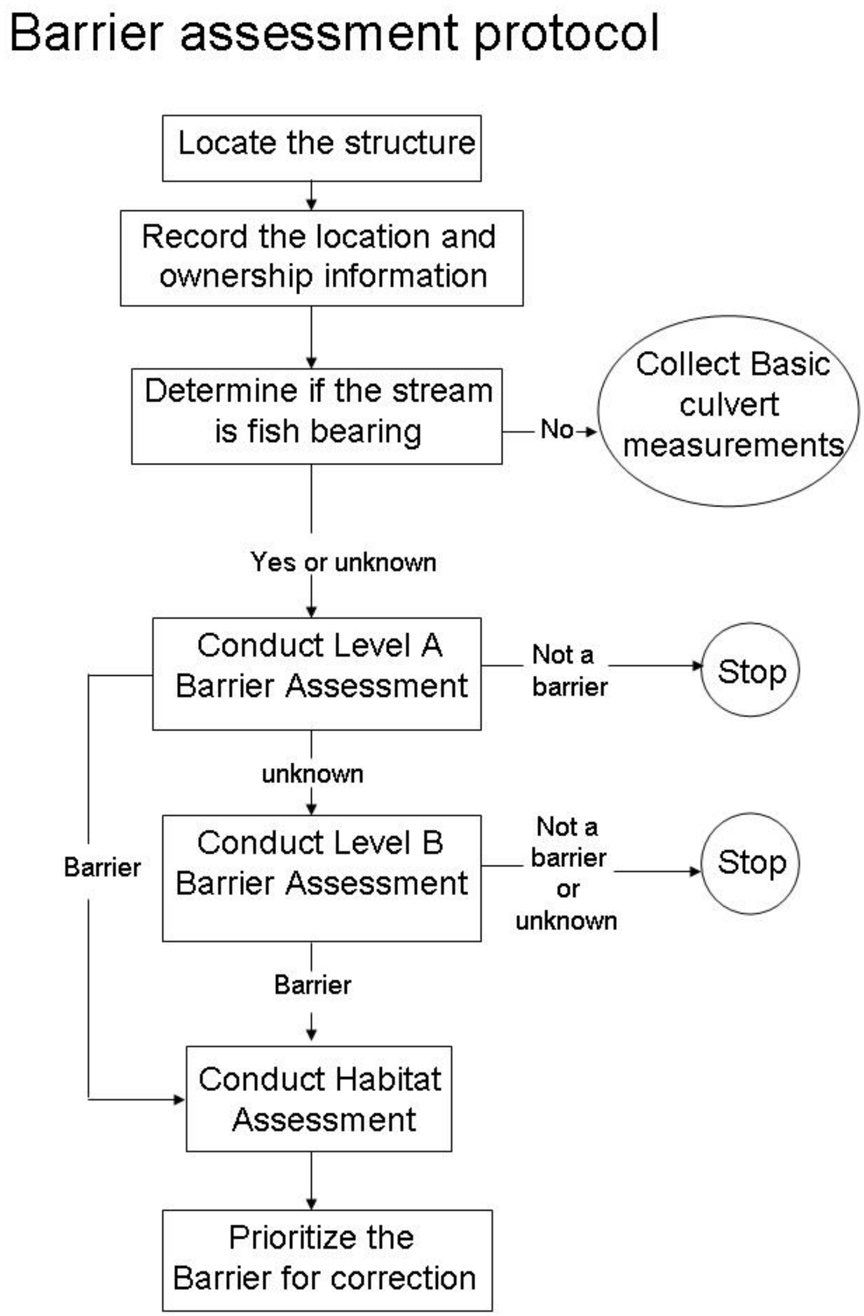

Figure 1. Steps of the fish migration barrier assessment protocol as developed by the Washington Department of Fish and Wildlife (WDFW, 2000).

- Water courses listed as fish bearing in “A catalog of Washington streams and Salmon Utilization”.
- Water courses listed as fish bearing on StreamNet (http://www.streamnet.org/).
- Water courses with documented salmonid use determined by visual observation, electrofishing, or verification by local biologists.

If it is deemed that the stream can not maintain viable populations, a simple survey of the physical characteristics of the structure is conducted. If it is considered that the stream is able to support fish, a more in-depth survey of physical characteristics is conducted to provide information necessary to assess the porosity of the barrier to the movement of fish. At this stage a “Level A” assessment is made during which the information collected by the field crew includes descriptions of structure features (e.g., culvert shape: arch, round, box, ellipse etc.); material from which the structure is composed; measures of horizontal and vertical dimensions of structure and ratio of these dimensions to the stream channel; water depth; length; slope; outfall drop and dimensions of plunge pool (if culvert); field estimate of water velocity (using a flow meter); presence of an apron or tidegate; maintenance required; results of subjective fish passage evaluation (yes = structure is a barrier, no = structure is not a barrier, or unknown); percentage passability based on professional judgement of field crew (values = 0, 33, 67, or 100); repair status based on professional judgement (e.g., if not a barrier = OK; repair not warranted due to insufficient habitat gain = NG; repair required, RR, if sufficient habitat gain would be achieved; or undetermined = UD); and recommendation for a future site visit (WDFW, 2000).

If, after a Level A assessment, it remains difficult to determine the barrier status (passable or impassable) of the structure (e.g., because the structure creates a hydraulic barrier), a “Level B” analysis must be completed. During a Level B analysis, information needed to model hydraulic conditions are collected. For example, if the barrier being considered is a culvert, additional information required includes culvert and streambed elevation at the upstream and downstream ends; if corrugated sheet material is used, the dimensions of the corrugation to be used in a hydraulic model to determine roughness coefficients; downstream control cross section (the downstream control may be the head of the first riffle below the outflow); downstream control water surface elevation; water surface elevation 15 m downstream of the control point; and dominant channel substrate. The Level B hydraulic analysis is used to calculate maximum velocity and corresponding depth within the barrel of the culvert under high flow conditions relative to defined fish passage criteria for the target species or family and life-stage (e.g., adult trout) (WDFW, 2000).

All information collected during the field assessments of the barriers is sent to the WDFW who maintain a central repository of data known as the SSHEARBase (WDFW, 2000).

Based on estimates of potential habitat gain (see habitat assessment section) as a result of barrier mitigation or removal; the status of populations that would benefit from increased access; the ability of the population to gain access (termed mobility); and the financial cost of repair, a Priority Index is developed for each structure (WDFW, 2000). This Index is used during the decision making process in relation to prioritization, taking into account other social and political constraints.

Using datasets for barrier culverts located in Washington State, O'Hanley and Tomberlin (2005) employed powerful optimization modelling techniques to define the most efficient solutions to prioritization of barriers for removal or mitigation, and then compared the model outputs with heuristic and more traditional "scoring and ranking" methodologies. The optimization models used integer programming techniques to develop a novel decision-making approach that could be used to form barrier mitigation and removal decisions based on information on a fish passage barrier network. The overall methodology was termed the Fish Passage Barrier Removal Problem (FPBRP) and three alternative problem solving solutions were assessed.

The dynamic programming (DP) formulation was devised to find a global optimal solution for mitigation and removal of barriers. Using this methodology, the fish passage barrier network was defined as a “tree” structure (Fig. 2) in which a “node” represents a barrier. In the most simple example, nodes can be further categorized as a “parent” (with at least one upstream node incident to it); “child” (incident to a parent); and “siblings” (groups of nodes having same downstream parents). When more complex fish passage barrier networks are considered the designation of nodes on the tree structure becomes more convoluted, consisting, for example, of “childless” and “terminal” and “nonterminal” “leaf” and “branching nodes” (see O’Hanley and Tomberlin, 2005, for more explanation). The use of the tree structure is a simplification of reality as it assumes that streams never diverge as they flow downstream and, therefore, does not model braided or anastomosed stream systems. Nevertheless, the DP modelling methodology, that starts with the uppermost layers of the tree and works downwards, finds a solution to the problem by breaking the problem down into smaller components, which are then solved in an iterative manner (O’Hanley and Tomberlin, 2005). Ultimately an optimal solution, based on assigned costs (e.g. financial burden of removal of the barrier or provision of fish pass) and benefits (e.g., resulting area of habitat made available) of barrier mitigation / removal, is achieved.

The Heuristic method is a problem-solving technique in which the most appropriate solution of several is selected at successive stages for use in the next step. In this case, the method used was based on an alternative modelling approach that utilised “greedy type” algorithms for integer programmes designed to provide rapid solutions of reasonable quality. The solution was calculated by iteratively setting a decision variable with the highest “utility” (benefit-to-cost ratio, usually weighted net habitat gain relative to repair cost) so long as the cost of the variable did not exceed the remaining budget (O’Hanley and Tomberlin, 2005). The authors referred to the heuristic method as the “greedy add with branch pruning” (GABP) which used a greedy adding procedure to construct an initial solution, and then iteratively attempted to improve on this solution through the use of local search techniques referred to as “branch pruning” (Fig. 3). During

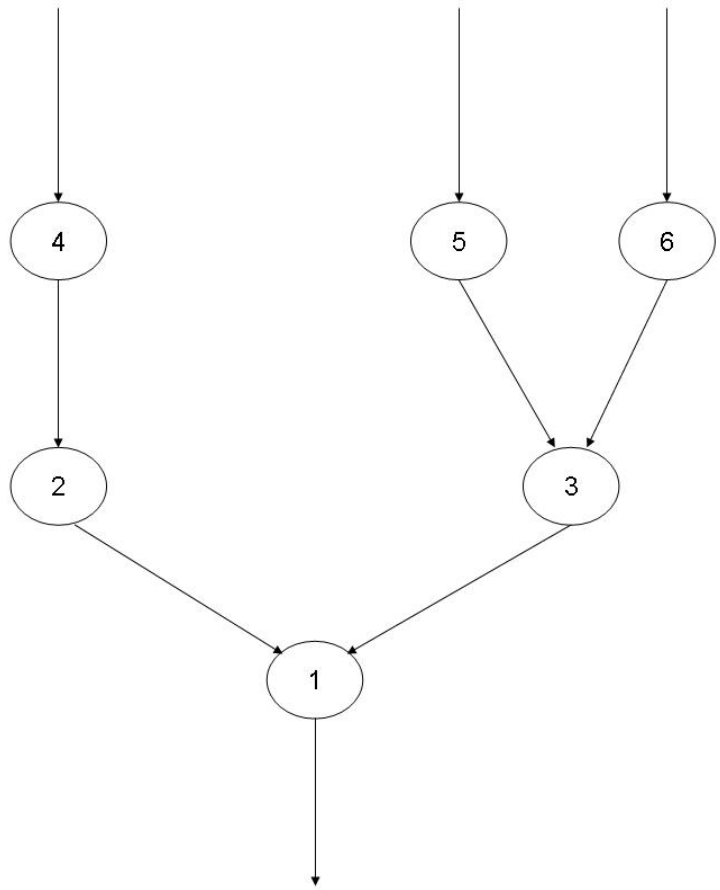

Figure 2. Fish passage barrier network forming the basis of optimization modelling techniques proposed by O'Hanley and Tomberlin (2005). Barriers are represented by nodes and arrows indicate direction of flow and area of stream habitat between barriers. Node 1 is the "parent" of "child" nodes 2 and 3 which are thus "siblings". Node 4 is the "child" of "parent" node 2. Nodes 6 and 4 are referred to as terminal leaf nodes, and node 5 a nonterminal leaf node. For more information see O'Hanley and Tomberlin (2005).

each iterative stage, the benefit-to-cost ratios were calculated for all affordable (i.e. within budget) repairs and the solution with the highest value gain was selected. During the process, the presence of impassible downstream barriers were taken into account. Once a solution was obtained, further iterations took place during which branches of the network were selected and “closed” and the costs savings from “unrepairing” were fed back into the calculations (and the budget) and alternative scenarios analyzed in an effort to find an improved solution.

Scoring and Ranking systems represent the most common method for prioritizing barrier mitigation and removal projects (e.g. Pess *et al.*, 1998). Scores are simply assigned to each barrier according to physical, ecological, and economic attributes that describe habitat quantity and / or quality; measure of improvement to fish movement as a result of mitigation; and cost of mitigation. Thus a cost: benefit ratio is calculated. Barriers are then assigned a rank based on the cost: benefit ratio, and prioritization for mitigation or removal is considered based on systematic consideration of the ranked barriers within financial constraints. That is, mitigation is achieved by selecting barriers in decreasing order of rank until the budget is exhausted (O’Hanley and Tomberlin, 2005). While scoring and ranking systems are relatively simple and straightforward to implement and require virtually no computational effort, the major weakness of this approach is that barriers are considered independently of each other and their spatial arrangement. Scoring and Ranking systems assign scores and ranks to barriers based on information that does not consider the porosity of upstream and downstream barriers. This can result in highly inefficient solutions in which the mitigation of upstream barriers occurs before impassable barriers downstream and potentially no net gain in habitat for the target species of interest (O’Hanley and Tomberlin, 2005).

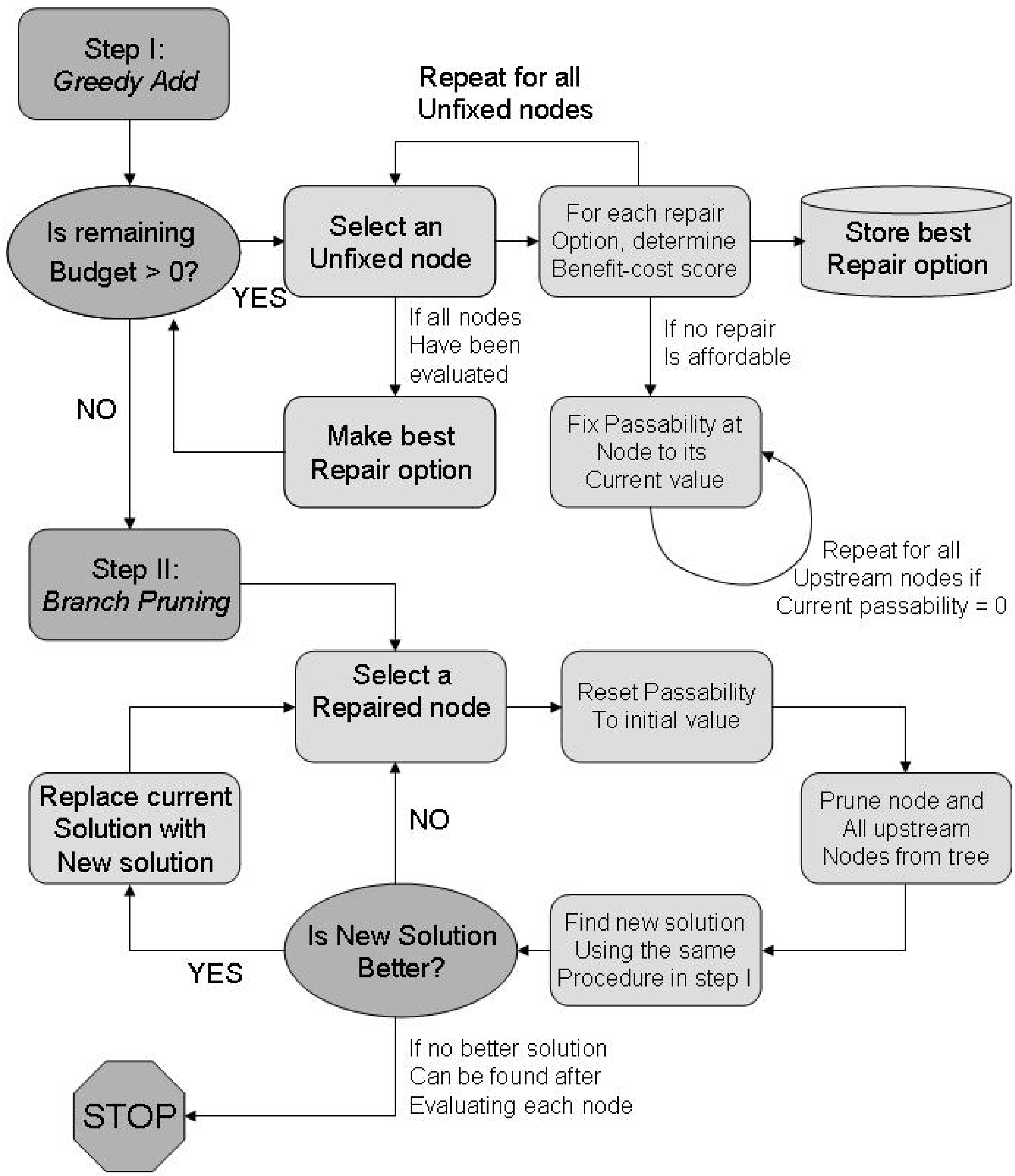

Figure 3. Protocol for heuristic GABP methodology (from O'Hanley and Tomberlin, 2005).

The results of comparing the three alternative methodologies using eight real datasets for culverts in Washington State (O'Hanley and Tomberlin, 2005) indicated that the most effective approach was to produce the global optimal solution (involving several hundred barriers) provided by DP usually with a solution time of less than half a second. The GABP heuristic method also gave adequate results, usually within a few percentage points below the optimal solution, and with relatively low computational effort. The Scoring and Ranking system that prioritizes mitigation based on cost: benefit ratios frequently produced solutions that were significantly suboptimal (e.g., 25 – 100% below the maximum).

Although the benefits of using optimization techniques suggest that they should be fully considered as a prioritization tool for use within the British Isles, a potential drawback is the level of technical complexity involved and the requirement for mathematical and computer programming expertise. Some may also argue that optimization modelling techniques are less effective when knowledge of the fish passage barrier network is relatively incomplete or uncertain. However, the completeness of the fish passage barrier network data and the method for selecting which barriers to mitigate or remove can be thought of as separate issues (David Tomberlin, pers. comm.). A simulation method could be employed to capture uncertainty about the true universe of barriers (e.g., extent to which they impede flow or migration, estimated cost of repair, or location in network) by using the existing data to generate artificial data sets. Optimization or sorting and ranking techniques could be applied to the artificial data sets to subjectively estimate how prescriptions for prioritization vary with the true (unknown) barrier universe. Analysis of a sample of the known dataset could be used to provide a reasonable range of values for specific parameters such as distance between barriers, or cost of barrier mitigation. These parameter ranges could be used to artificially generate a number of new barrier data sets, to each of which the prioritization scheme (optimization or other) could be applied in order to obtain a subjective estimate of the range of possible performance outcomes (and hence a risk metric). This approach could form the basis of a cost: benefit analysis for further improving the inventory of barriers. Alternatively, there may be some potential in the application of alternative stochastic optimization techniques (e.g., Bayesian or a stochastic programming approach). However, it could also be argued that the use of solution algorithms for randomly generated datasets to obtain performance outcomes will likely show little more than the results presented by O'Hanley and Tomberlin (2005) and does not address the core issue related to the uncertainty on the number, location, and porosity of any intervening barriers between known impediments. It is likely that a heuristic procedure or ranking scheme would need to consider the distance of a barrier to the sea or nearest mainstem river. The development of an optimization model may be possible, but would require considerable effort to adequately incorporate the key stochastic issues (see section 9.4 for further discussion). The development of optimization models, either using a Baysian or stochastic approach, will require additional research and development in this field and will likely bring added benefits to the current project over the long term.

An optimization modelling approach was also developed by Kuby *et al.* (2005) to demonstrate the benefit of using techniques that holistically consider dam networks versus those that narrowly focus on removal or repair on a dam-by-dam basis. The multiobjective optimization model developed was based on two key elements. First, multiobjective programming enabled analysis of ecological and economic tradeoffs associated with dam removal. The ecological objectives were to maximize habitat connectivity for salmonids, while the economic objectives were to minimize lost hydropower generation potential and water storage capacity. Second, the model considered the relationship between upstream and downstream dams, and thus the fish migration barrier network as a whole, rather than independent components. Kuby *et al.* (2005) used a case study based on the Willamette River (Oregon) catchment as a means to illustrate the validity of this approach (rather than to inform management decisions) for the prioritization of dams for removal, or in a variant model, to highlight the impact of varying fish passage efficiency of bypass systems on connectivity.

The model outputs were L shaped Pareto-optimal tradeoff curves that depicted a spectrum of solutions ranging from one extreme, where the solution minimizes economic loss at the expense of habitat connectivity, to the other in which habitat reconnection is maximized at the expense of economic services (Kuby *et al.*, 2005). Based on the case study, a significant tradeoff was illustrated in which the removal of 12 dams resulted in the reconnection of 52% of habitat within the catchment at the expense of only 1.6% of hydropower and water storage capacity. From this point at the elbow of the tradeoff curve, however, increased ecological benefit resulted in increasingly steeper economic costs. The authors take great efforts, however, to emphasize that the model was designed to illustrate the strengths of optimization techniques, and that the results should not be used to form management decisions because a multitude of other factors were not considered. For example, the study considered only habitat gain in terms of quantity, and did not distinguish suitable habitat for salmonids. Also, the study only addressed hydropower and water storage, and ignored other important economic factors (e.g. recreational value of reservoirs) or the costs of removal. Nevertheless, future iterations of the model could potentially accommodate these, and other, additional factors. The multiobjective programming methodology is not intended to generate a single recommendation as economic and ecological objectives are not weighted. Instead, the tool provides a mechanism of prioritization that may facilitate the decision making process when evaluated by experts.

The state of Oregon is currently developing *The Oregon Fish Passage Barrier Data Standard* (OFPBDS) as a mechanism to document and build an inventory of geospatial fish passage barrier information (ODFW, 2007). The model is intended to act as a central repository of fish passage barrier data that is currently held by disparate groups. The OFPBDS will facilitate the standardization of datasets so that future data acquisition is consistent and will allow compatibility of datasets (ODFW, 2007). This GIS based system will focus on a core set of geospatial information to form a database of location and geometry of the barrier. The OFPBDS will characterize and document both current and potential barriers of a variety of types, both natural and anthropogenic (e.g., dams, culverts, bridges, tide gates, weirs, falls, cascades, and gradient barriers), for upstream and downstream migrating fish (ODFW, 2007). The OFPBDS will be made available to multiple end-users including government agencies, industry, and the general public. The OFPBDS will facilitate future programmes of prioritization of barriers for mitigation or removal because it will form a comprehensive inventory at the statewide level. To model the impacts of barrier removal it is preferential to construct as detailed a picture as possible of as many barriers within the system. This methodology currently remains at the developmental stage and provides a good example of the utilization of GIS technology to create a geospatial inventory of structural impediments. This may provide a useful template for British Isles agencies (e.g. Environment Agency [EA] and Scottish Environment Protection Agency [SEPA]) that currently maintain a considerable GIS expertise base. It is not clear, however, how barrier porosity is determined based on fish passage criteria (swimming capabilities and/ or behaviour) and for which species. It is also not clear at this stage how the datasets will be analyzed to facilitate prioritization of barrier mitigation or removal. The methodology currently considers only physical geometry of the barriers, and does not consider hydraulics (ODFW, 2007), although there may be future plans to do so.

In California, state legislature (The Salmon, Steelhead Trout, and Anadromous Fisheries Program Act, 1988) required that efforts be directed by the Department of Fish and Game (DFG) to significantly increase the natural production of Pacific salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) (CSCC, 2004). As part of this ongoing programme, several state and federal agencies expend considerable resources collecting, collating, and analyzing a variety of fish and aquatic habitat data including information on barriers to fish migration. One of the most significant challenges is to reduce the probability of duplication of effort and to bring the information together at one central point which all stakeholders can access. By centralizing access to California's fisheries data, the potential to standardize the data and identify gaps in knowledge is enhanced. “CalFish” is a cooperative programme that brings together multiple agencies and other stakeholders in an effort to collect, standardize, maintain, and provide access to a range of databases relating to fisheries and habitat. It is novel in that it utilizes the world-wide web to disseminate information in an interactive way in which users can query either database tables directly or geographically via an interactive on-line mapping system. Users are also invited to send additional information to the co-ordinator. CalFish maintains a comprehensive and up-to-date list of links to a wide variety of fish and aquatic habitat data programmes and other relevant web sites including the California Passage Assessment Database (PAD) project.

The PAD project is a multi-agency initiative funded by the Coastal Conservancy and compiled by the Pacific States Marine Fisheries Commission to collect, collate, standardize, and synthesize available data on fish passage barriers at a State-wide level. The other agencies involved are the California Department of Transportation; DFG; Department of Water Resources; The Fish Passage Forum; Institute for Fisheries Resources; NOAA Fisheries; Trinity County; and the United States Forestry Service (CSCC, 2004). It was developed to provide a common framework for the collection, management and analysis of data relating to potential barriers and to then present that data in an easily accessible format. Key elements of the data collected include location, ownership, structure type, and the degree of impassability.

The PAD project has been conducted over four phase: (i) identify and contact sources of available information of potential fish barriers; (ii) collect data from identified and any other new sources of information; (iii) assemble a team of data technicians and GIS experts to identify areas where data was lacking and how it might be improved, and to develop the PAD structure, strategy for peer review, and outreach mechanisms to elicit the help of stakeholders to collect additional data; and (iv) develop fish passage improvement projects with local partners (CSCC, 2004). By obtaining information from a variety of sources, including existing databases or by conducting additional surveys commissioned by the Conservancy, a map-based (GIS) inventory of potential barriers to fish movement is continually being developed, primarily concentrating on Pacific salmonid (salmon and steelhead) species. The majority of original sources of information are themselves converted to electronic files and archived (e.g., StreamNet library at the University of California Berkeley Water Resources Center Archives).

Using the informational available, each barrier is categorized based on type and passage status (degree of impassability). The PAD Defines 14 types of potential barrier or site (PAD, 2008): dam; road crossing; utility crossing (utility line e.g. water or gas that crosses a channel and potentially impedes movement); diversion (e.g. abstraction for irrigation or off-take for hydropower); flood control channel; grade control (stabilizing weirs that prevent erosive lowering of the channel bed); flow measurement or gauging weir; gravel pits; fish passage facility; non-structural (natural barriers); tidegate; fish trap; other (any structure not included in above list); and unknown (database does not specify structure or site). Eight categories of passage status, considering anadromous salmonids, have been defined (PAD, 2008). These are as follows:

- *Total*: a complete barrier to fish passage for all anadromous species at all life-stages at all times of year.
- *Partial*: only a barrier to certain species or life-stages.
- *Temporal*: only a barrier at certain times of year.
- *Temporal and partial*: only a barrier to certain species or life stages and only at certain times of year.
- *Temporal and total*: total barrier only at certain times of the year.
- *Not a barrier*: structure/ site has been determined not to be a barrier to any species or life stages, and is passable year-round.
- *Structure may not still be in existence*: data obtained from an old dataset, and are likely to have been removed or washed away.
- *Unknown*: dataset had no information about barrier status.

The PAD system requires that the data be standardized and stored in one central repository. It is also intended that the PAD be compatible with other related data sources. Using GIS, information relating to potential barriers is stored in a *shapefile* by digitizing the locations (latitude and longitude coordinates) of the structures or features along the channel (PAD, 2008). Each record is indexed to an existing National Hydrography Dataset (NHD) developed by the United States Geological Survey (USGS) at 1:24,000 scale (PAD, 2008). The NHD is basically a database of flow-networked stream reaches. Other databases that are also based on this standardized hydrography data are thus immediately compatible with the PAD. The PAD is also supported by other modules, including the *Fish Species Module*, that provides information on passability (relative to modelled stream flow) specific to particular species or life-stages relative to the direction of migration (upstream versus downstream) and swimming and leaping abilities. Therefore, for each single barrier data point, multiple specification layers are available reflecting the several species that may be impacted by its presence (PAD, 2008). Further, observation based fish distribution data is used to overlay the PAD. The fish distribution data, compiled from several sources, consists of positive observation of coho salmon (*O. kisutch*) and steelhead trout. This information may, however, underestimate actual fish distribution. The PAD system is also supported by the *Water Diversion Module* which provides information from the *Fish Screen and Fish Passage Program* and *Water Rights Information System* (State Water Resource Control Board) related to an inventory of screened and unscreened diversions and associated fish protection facilities and data on water rights applications and related permits and licences (PAD, 2008). As of the time of publishing the *Inventory of barriers to fish passage in California's Coastal Watersheds* (CSCC, 2004) in excess of 13,000 sites had been identified, of which over 3,300 were designated as passage barriers, 636 were not known to be barriers to fish migration, and more than 9,000 require further examination to determine passage status.

Despite a coherent approach to collate and maintain a single source of data related to the presence of potential impediment to fish migration, there remain considerable challenges associated with standardization and data quality (PAD, 2008). The PAD is based on a large number of data sources that were originally created for a wide range of purposes. As a result there is spatial (regional) variability in the availability of fish barrier data and, thus, insufficient or missing information; often a lack of the necessary precision (e.g., related to exact location of the barrier or site); and potential for overestimation of the number of barriers due to the listing of the same barrier in several datasets (PAD, 2008). Nevertheless, and in spite of these problems, the development of the inventory continues and the quality of data is consistently improved.

Barriers are ranked for severity of impact to fish passage, historically based on expert judgement (CSCC, 2004), and recently depending more on criteria recommended by the California Department of Fish and Game (California Salmonid Stream Habitat Restoration Manual). Barriers are usually given severity ranks such as very high, high, fair, medium, low, or none. Prioritization of barriers for removal or mitigation tends then to be considered from both catchment and regional perspectives, and considers both position within the river network and magnitude of benefit relative to river distance (quantity of habitat) made accessible. At a catchment scale, the first most downstream man-made complete impediment is designated as the “Keystone” barrier (PAD, 2008). It may be argued that a less severe barrier on a relatively high order river may be a higher priority for mitigation or removal than a severe barrier in the upper headwater reaches. Parameter such as “stream miles to next barrier” and “stream miles to anadromy limits” (i.e., an end-point to upstream migration) are also quantified and taken into consideration. At the regional scale, ranking and prioritization become more difficult as social and political constraints become increasingly significant. For example, there is currently debate as to whether limited funds should be directed at catchments where fish populations are the most critically threatened (e.g., central and southern California), or to concentrate on areas where populations are more robust (e.g., northern California) and likely to result in a higher return rate when considering increases in productivity (CSCC, 2004). Ultimately, however, the large scale prioritization mechanism continues to depend, at least partially, on expert judgement taking into consideration factors such as the identification of “key catchments” based on conservation efforts (e.g., where a State Coho Recover Plan or Southern Steelhead Resources Project is underway). Barriers are then prioritized based on position within the catchment with the mitigation of those on higher order streams and rivers resulting in greater benefit. Thus, there is a two tier approach by which an assessor assigns a prioritization rank to the barrier itself, and expert judgement is required to consider that from a catchment and statewide context (Michael Bowen, State Coast Conservancy, pers. comm.)

An important component of the PAD project is the requirement to ensure that the inventory developed is widely disseminated to all stakeholders and interested parties. It is made available to the public via the CalFish website (www.calfish.org), and PAD administrators actively request reviews and feedback to be sent to the PAD team. This mechanism of dissemination also ensures that the data-base is improved by the process of peer-review by appropriate agencies and other organizations / individuals, and provides a facility by which additional information can be acquired. To this end, the system has recently provided a “PAD review tool” that allows the database to be edited on-line. This concept, if successful, may prove to be an efficient means of attracting information that would otherwise be costly or difficult to obtain. However, there may be concerns related to standardization of barrier assessments and associated data quality if inadequately trained personnel provide additional material.

The Federal US Fish and Wildlife Service have developed nationwide methodology that is similar to that for the CalFish PAD project. The Fish Passage Decision Support System (FPDSS) is based on an (incomplete) inventory of potential barriers provided by multiple local, state, and federal sources. The fish passage status of the barriers has not been rigorously assessed beyond the information provided by the various source datasets. The inventory data of potential fish barriers is mapped on to the NHD (1: 100,000 scale) and a modelling tool enables users (e.g., decision and policy makers) to assess the result of removal of a sequence of barriers in terms of stream distance made accessible. The model calculates the total stream distance in both upstream and downstream directions, including tributaries, between barriers or the stream end point. The methodology is spatially limited by the extent of the NHD, and by the fact that the base units are the stream “reach”. Any single reach may contain more than one barrier, and barriers do not neatly occur at the end of stream reaches. As a result, under or overestimates of stream distance made accessible by mitigation or removal will occur. The methodology is also relatively simplistic, as habitat quality, and conservation, social, political, and financial factor are ignored.

On the Eastern seaboard of the United States, state and federal agencies, along with non-governmental national and local organizations have started to develop inventories of barriers to fish migration to facilitate prioritization of passage improvements projects. As is the case elsewhere in the United States, considerable attention has been directed at culvert barriers, which are particularly relevant in regions with a high population density and abundant road networks such as the northeast US. Unfortunately, the variety of methods used by different organization creates the strong risk of duplication of effort, both in the development and in the application of assessment protocols. Further, several methodologies that have been developed have not been sufficiently validated e.g. by employing marking or telemetry studies (Keith Nislow, USDA Forest Service, pers. comm.).

The US Forest Service, because of its responsibility to manage road infrastructure on National Forest land holdings in an ecologically sound manner, has had a long interest in targeting and remediating road crossings that are barriers to aquatic organism passage. More than a decade ago, engineers and scientists developed a simulation tool called ‘FishXing’ (Love *et al.*, 1999; Furniss *et al.*, 2006 http://www.fsl.orst.edu/geowater/FX3/FX3_manual.pdf)) that can be used to predict whether critical fish swimming speeds will be exceeded at road culverts. However, this model requires detailed hydrologic data that are unavailable at many sites, and has not been extensively validated in the field. A “Coarse Filter Assessment Methodology”, based on Coffman (2005), and supported by the USDA Forest Service National Aquatic Ecology Office is an exception to the latter point as validation was an important component during the design phase. Coffman (2005) developed models to predict whether culverts were passable or impassable based on physical characteristics (e.g., perch height, slope, width, presence of a downstream pool) and a literature review of swimming and leaping capabilities for three groups of stream-dwelling fish species. The three groups; *Salmonidae* (trout) (Model A); *Cyprinidae* (minnows) (Model B); and *Percidae* (darters) and *Cottidae* (sculpin), (Model C), were categorized, based on body shape and fin morphology and position, to represent three swimming 'guilds' (salmonid, midwater, and benthic). A series of mark-recapture studies at 26 road-crossings in the States of Virginia and West Virginia were used to validate the model facilitating the identification of failings and improvements. Although it was possible to predict passability of specific culverts, as fish movement was negatively correlated with culvert gradient, gradient x length, and velocity (for cyprinids), it should be noted that as a general rule, all culverts were found to impede fish movements.

The Coffman (2005) study did not develop a prioritization mechanism to aid decisions for barrier mitigation or removal, but has subsequently formed the basis of a methodology currently being deployed on National Forest lands east of the Mississippi River (Keith Nislow pers. comm.). While the methodology primarily considers species of fish, it is novel in that it also considers the passage of other aquatic organisms at road crossings (i.e., culverts and low water fords) (Nislow and Mendez, 2007). Typically, the process starts with the determination of target catchments for assessment based on the following specific criteria:

- Little to no information available for specific management decisions.
- Superficial information available but not detailed enough for specific management decisions.
- Presence of known sensitive or listed species contained within identified catchment.
- Strong partnership with other federal, local and state agencies allowing for integrated management schemes.

Once the target catchment is identified, specific geospatial information is collected and processed by National Forest personnel primarily based on topographic data within the boundaries demarked on maps of National Forest land. GIS layers of roads and streams within the target catchment are developed and used to create a point layer that contains digitized points representing locations where roads and streams intercept and thus identify the positions of potential barriers that should be surveyed. The GIS point layer is supported by a background database that contains specific data related to the individual points such as site identification code, type of structure (e.g. vented ford, pipe arch culvert, box culvert), ownership, total number of associated streams, and total upstream length. A pragmatic approach was adopted to maximize assessment efficiency within the constraints of limited resources. Surveys were restricted to culverts and low water fords based on the assumption that bridge crossings do not usually present a significant barrier to aquatic organisms. Several channels were dry during the period of assessment in those catchments characterized by a predominantly limestone geology. These channels tended not to be considered during assessments. Crossings on channels with a stream order of 3 or higher are given greater priority based on the premise that barriers sited on higher-order streams have the potential to block a disproportionately larger area of habitat. Further, the decision whether to assess those rivers that form part of the catchment, but are situated outside of the National Forest boundaries, remain the responsibility of the National Forest Authorities (Nislow and Mendez, 2007). It is important to note, however, that the inventory developed does not necessarily reflect a complete fish passage barrier network for the above reasons, thus resolution of prioritization may be limited.

The development of the inventory followed the National Inventory and Assessment Procedure (NIAP) for road – stream crossing (Clarkin *et al.*, 2003). Sites identified using topographic maps and GIS layers are inspected and presence of a barrier confirmed. Locations of barriers not previously identified using the mapping techniques are recorded using GPS and assessed. Data collected during surveys include a longitudinal profile of channel gradient using standard surveying techniques; digital photograph of inlet and outlet of the structure; a site sketch; and GPS coordinates. The methodology results in an inventory of identified crossings; less catalogued; and less still surveyed. Then, by using the Coffman (2005) method, a percentage value is obtained to describe the passage efficiency of the specific structures for the three stream fish guilds.

While the above-mentioned protocols identify possible candidate crossings for removal or remediation, they do not of themselves provide much information on where passage improvement efforts should be focused. Methods of prioritization are currently being further developed along several lines. At the most basic level, priority can be based on measures of increased barrier-free corridor length achieved by removal relative to the presence of downstream barriers (Keith Nislow pers. comm.). The use of GIS as part of this methodology has important implications for later prioritization of barriers for rehabilitation. Using analysis of GIS data, barriers can be grouped in an effort to assess the cumulative effects within the stream network and allow comparison between catchments. At the same time, efforts are being made to better incorporate differences in habitat quality, along with studies of the effects of population fragmentation on demography and genetic diversity (Letcher *et al.*, 2007). Further, particularly in the western US, there is concern and ongoing research dealing with the relative impacts of barriers to movement on native fish populations compared to barrier removal increasing the risks from invasive species (Fausch *et al.*, 2006).

Methods of prioritization are currently being further developed. It is likely that prioritization schemes will be based on measures of increased barrier-free corridor length achieved by removal relative to the presence of downstream barriers and information on populations (Keith Nislow pers. comm.). The use of GIS as part of this methodology has important implications for later prioritization of barriers for rehabilitation. Using analysis of GIS data, barriers can be grouped in an effort to assess the cumulative effects within the stream network and allow comparison between catchments.

In the State of Maine, NOAA fisheries are coordinating an initiative that is in the early stages of developing a similar methodology to create an inventory of barriers on the Penobscot River as part of a larger river restoration project (Rory Saunders and Tim Sheehan, NOAA, pers. comm.). The Penobscot River remains an important system for a remnant population of Atlantic salmon (*Salmo salar*) that are listed under the Endangered Species Act. As part of the restoration programme, two of the lower most mainstem dams will be removed, and one of the tributary rivers partially removed. The removal of these dams was based more as a result of political decisions rather than due to the outputs of a prioritization model. It is recognized, however, that the removal of these large hydropower dams must be reinforced with further action and hence a programme is underway to develop new tools to create an inventory of barriers and facilitate prioritization for removal. Although the principle driver has been the political and economic significance of Atlantic Salmon, the project considers multiple species including the river herring species (e.g., alewife [*Alosa pseudoharengus*]), tomcod [*Microgadus tomcod*], American eel [*Anguilla rostrata*], and sea lamprey). However, as little information is known of fish passage criteria, life history, timing and extent of migration, and habitat suitability and availability, the project concentrates on 4 or 5 "umbrella" species for which sufficient information may be available. This is based on the premise that if you improve conditions, e.g. for Atlantic salmon, then you will also improve those for multiple species.

In relation to assessment of barrier porosity, it is recognized that the project will be based on an incremental methodology, that will first depend on an incomplete inventory of barriers (starting with those in the lower river) and subjective assessments of fish passage efficiency. This is in part based on the fact that, for several species, fish passage criteria are not currently available, and the need to implement restoration efforts before a complete inventory is achieved. At some of the large dams, data relating to fish passage efficiencies for Atlantic salmon have been provided by radio-telemetry studies. Estimates of fish passage efficiencies for other large dams will be based on literature reviews of fish passage efficiency at "similar" analogous dams.

Although considerable amounts of data currently exist, they are held by different state agencies. It is proposed that NOAA will collate the data and hold it in one federally maintained database. The programme will facilitate better co-ordination between the various stakeholders to ensure that there is potential for overlap between projects so that greater benefits are realised for multiple species. Although the relevant information could be held on either an Access or Excel database, the preferred option is to develop a GIS based system. The potential for employing a GIS based tool for prioritization of barriers for removal or mitigation is considered limited until a complete inventory of barriers within the catchment (based on good quality fish passage criteria) and availability of habitat for multiple species has been achieved.

5.2. Europe and the British Isles

Throughout Europe, considerable efforts to determine the passability of structures to migratory fish have employed empirical radio-telemetry techniques directed at salmonids and large scale hydropower projects (e.g., Chanseau and Larinier,1998; Gowans *et al.*, 1999, 2003; Rivinoja *et al.*, 2006). With some notable exceptions (e.g., Ovidio and Philippart, 2002; Ovidio *et al.*, 2007; Winter and Van Densen, 2001), studies that focus on non-salmonids and / or small-scale barriers tend to be relatively uncommon. While empirical studies provide valuable information at the local scale, it is recognized that there is a need to develop national inventories of barriers to facilitate prioritization for management purposes.

In Belgium, Ovidio and Philippart (2002) used radio-telemetry to assess the impact of a range of structural impediments on fish migration in the River Ourthe system. Potential barriers were classified based on physical measurements (e.g. slope, length, and height), on the movement of several species of fish (brown trout, [*Salmo trutta*], grayling, [*Thymallus thymallus*], Atlantic salmon, nase [*Chondrostoma nasus*], barbel [*Barbus barbus*], and Pike, [*Esox lucius*]). Ovidio *et al.* (2007) built on this approach by assessing the ability of trout and grayling to pass small-scale barriers (falls and chutes) on three tributaries of the River Meuse using radio-telemetry and comparing this with simple topographical descriptions of the structures. The authors recognized the need to collect information on barriers to fish migration to plan restoration efforts to reconnect fluvial habitat by prioritizing problematic sites that have the greatest negative impact. Fish passage over the structural impediments was monitored for each species taking into consideration water temperature and flows. Conservative values for the percentage time the barriers were passable using temperature and flow data were estimated, thus potentially providing a measure of temporal fish passage efficiency.

Driven by the target to provide free fish migration in Flanders by 1 January 2010, as set under the Benelux Decree (1996), the Flemish Environment Agency have developed a database of obstructions to fish migration (Monden *et al.*, 2000) which can be interrogated via the web (www.vismigratie.be). The database of obstacles has been used to develop a priority map to help decision makers implement a barrier mitigation programme, either by the removal of the structures, or the provision of fish passage facilities (weirs and pools and nature-like bypass systems) (Johan Coeck, Research Institute for Nature and Forest, Belgium, pers. comm.). Watercourses in contact with the sea and those considered to have greatest value and strategic importance were given priority and 3,000 km of river length has been identified for action (Kroes *et al.*, 2006). Basin management plans are implemented to meet the specific targets and depend on communication between the relevant water resource managers facilitated under Flemish legislation related to Integral Water Management. The strategy adopted provides a good example of a multi-national collaboration, as mechanisms to identify solutions were established with agencies in the Netherlands (Kroes *et al.*, 2006), where a similar web-based tool has also been developed (www2.vismigratie.nl).

In the Netherlands, Winter and Van Densen (2001) conducted an empirical assessment of the "porosity" of multiple weirs on the upstream migration of non-salmonid species (primarily cyprinids) in the River Vecht. The methodology used was interesting because it considered temporal and spatial variation in porosity. The temporal component was based on hydraulic measurements under fluctuating flow conditions, which when considered in terms of the swimming capabilities of the target species, enabled calculation of the number of days during which ascent could be achieved. Unlike more subjective approaches, the methodology required basic measurements of hydraulic conditions at the weirs. Assessments were based principally on three parameters: long term (23 years) daily records of water levels upstream and downstream of each weir; long term (18 years) daily discharge data; and results of a literature review on swimming capabilities of the different species and size ranges. Water velocities through the weir gaps under free flowing conditions were estimated by using simple relationships between discharge data and water levels. However, these estimates were supported by more detailed water velocity profiles which were measured at the weir gaps to provide finer resolution information related to near wall or bottom effects. Swimming capabilities were based on literature reviews of maximum burst speeds determined by the maximum distance covered by one tail beat (stride length) and maximum tail beat frequency (Wardle, 1975). Maximum stride length is species specific (e.g., Videler, 1993), whereas maximum tail beat frequency depends on species, temperature, and body length (Wardle, 1975). Therefore, this methodology requires information relating to each of these parameters, and does not consider the behavioural component (recognized by Winters and Van Densen, 2001; and discussed later in this report). Therefore, a measure of temperature during the period of migration of the specific species is required, and this itself is river specific. Without this information, simplistic assumptions must be made which is a limitation of the methodology, and may be of lower value than more subjective assessments under some scenarios. Indeed, the authors had to rely on assumptions of stride length and tail beat frequency for several less understood species. However, this method does have validity under certain site specific situations when more fine-scale information on fish passage efficiency is required, i.e. at critical sites dependent on calculations of costs versus benefits.

In Germany, the North Rhine-Westphalia (NRW) Fish Migration Programme aims to restore sustainable populations of diadromous species to the heavily modified River Rhine. This initiative is primarily driven by political will to restore populations of Atlantic salmon, although other species, including eel and lamprey, are also considered. A component of this programme requires the reestablishment of longitudinal connectivity between aquatic habitats. The River Sieg, an important tributary of the Rhine, is at the center of restoration efforts because it has relatively high water quality; historically maintained populations of salmon; and still maintains habitat that is suitable for salmon spawning. The federal state North Rhine-Westphalia and Rhineland Palatinate commissioned a report to analyse alternatives and recommend measures to restore connectivity of habitat for both upstream and downstream migrating fish (Dumont, 2006). The Seig maintains multiple barriers to fish migration, including six hydropower projects (Dumont, 2006). The report primarily relied on the evaluation of fish passage facilities present at the barriers based on guidance criteria developed by the German Association for Water Resources and Land Improvement (DVWK, 1996, translated to English in DVWK, 2002), and the development of suggested measures to improve longitudinal connectivity.

A methodology for the assessment of barriers to fish migration was developed by Ingenieurbüro Floecksmühle. Details of the methodology are provided in the Handbuch Querbauwerke (Dumont, 2005) and have subsequently been translated from German to English for the purpose of this review. The handbook recognizes that fish fauna are one of the biological elements on which classification of ecological status (Table 1) under the WFD is required, and to which evaluation of ecological effects of barriers and hydropower installations on rivers corresponds. A basic assumption is that to meet the minimum requirements of the WFD the river / water course must be passable so that there is connectivity between the respective river zones and from the source to the estuary in both upstream and downstream directions. Another basic premise on which this philosophy is based is that habitats are important to maintain stable populations of the relevant species and, therefore, must be no more than slightly affected by dams and water diversion systems.

Table 1. Definitions of ecological status classification of the Water Framework Directive (translated from Dumont, 2005)

Classification	Ecological status	Definitions
A	**High status**	The values of the biological quality elements for the surface water body reflect those normally associated with that type under undisturbed conditions, and show no, or only very minor, evidence of distortion.
B	**Good status**	The values of the biological quality elements for the surface water body type show low levels of anthropogenic alterations but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions.
C	**Moderate status**	The values of the biological quality elements for the surface water body type deviate moderately from those normally associated with the surface water body type under undisturbed conditions. The values show moderate signs of anthropogenic alterations and are significantly more disturbed than under conditions of good status.
D	**Poor status**	The values of biological quality elements for the surface water body type show major alterations and the relevant biological communities deviate substantially from those normally associated with the surface water body type under undisturbed conditions.
E	**Bad status**	The values of biological quality elements for the surface water body type show severe alterations and in which large portions of the relevant biological communities normally associated with the surface water body type under undisturbed conditions are absent.

Prior to ecological evaluation of fresh waters, information on dams and other barriers in North Rhine-Westfalia was collected and stored as the "Querbauwerke-Informationssystem (QuIS)". QuIS is a GIS (ArcView) based system that enabled graphical representation of the following:

- Hydrography in North Rhine Westfalia
- Catchment areas
- Gauging stations

- Topographic maps
- County area, e.g., administrative region, environment agency, district and independent cities and communities.

The development of the information system allowed effective storage and management to facilitate accessibility of information for the relevant authorities. The information system is based on extensive investigations of sites/locations of barriers and hydropower plants.

Barriers that meet the following two parameters are included in the information system:

1. Entire water area (catchment or sub-catchment) ≥ 10 km^2
2. Fall heights ≥ 0.20 m under mean flow

The evaluation of barriers and construction of QuIS was conducted in two geographical regions:

1. “Rechtsrheinisches Bergland (RB)“ (River basins Ruhr, Wupper, Sieg).
2. Flat country and “linksrheinisches Bergland” (remaining catchment area in North Rhine Westfalia).

The information system is based on multiple sources of information on barriers and hydropower station in North Rhine Westfalia. This included:

- Existing studies and data on barriers owned by authorities and organisations.
- Analysis of topographic maps (scale 1:5.000) for location of weir structures, mills, hydropower stations.
- Flood plain protection programmes.
- Surveys of potential hydropower sites.
- Additional literature on hydropower sites.

- Canoe guides.
- Literature on mills or historical information.
- Requests for data and other written information made to all relevant water authorities and associations.
- Data on water quality status.
- Maps of hydropower stations (WKN-Data), which was used to complement information obtained from other studies (e.g., water quality status data).

The collation of barrier information facilitated the identification of sites where their envirionmental impact could not be evaluated based on existing information alone. Sites that had a high restoration or hydropower potential were identified for future surveys. These were identified based on the following:

- Hydraulic height ≥ 0.20 m, < 1 m.
- Barriers with hydraulic heights ≥ 1 m.
- All barriers within the area affected by the governmental fish protection measures in North Rhine Westfalia.
- Barriers with a fish passage facility.
- Barriers with currently installed hydropower plant or with hydropower potential.

The database is designed to allow the collection of up to 60 data arrays for each site. It is possible to add information as free text (“comments”) to each relevant data array where needed, e.g. when numbers or standard-texts are not adequate. In addition, images are collected for each site visited and saved in the database. Data stored in the database was acquired from a variety of different sources. Before being merged, the plausibility of the data was checked and the decision made as to whether the data was acceptable.

Pertinent data collected at each site includes the following:

A. Location/site

- Type and name of river zone
- Spacing between barrier and estuary
- Community/County
- Catchment areas with name, size and number
- Next gauging station and relevant values for discharge
- Catchment areas of location/site
- Discharge of the location/site

Note that the flow rate of a site is automatically determined and integrated into the information system when there is a gauging station nearby.

B. Barrier data

- Owner
- Year of construction
- Status of barrier / structure
- Width
- Height
- Drop height
- Gradient
- Construction of barrier (permanent or movable)
- Material
- Type of gate (if available)
- Height of gate
- Width of gate
- Material of gate
- Height of the crest
- Width of the crest
- Mode of drive for gate or top
- Function of barrier (e.g., ramp, dam, hydro stations, water diversion)

- Length of impoundment
- Length of river diversion
- Discharge (minimum flow, maximum flow)
- Status and operation of building
- Information on fish passage facilities when water is diverted

C. Data on existing hydropower plant

(more than one hydropower station possible)

- Head height of the hydropower plant
- Flow rate
- Installed power
- Utilisation
- Status of the building
- Status of access route
- Grid connection
- Type of turbine (different type of turbines for a hydropower plant possible)
- Operating status of the turbine
- Type and status of the electrical components
- Information on the mechanical barrier for fish protection or the bypass at the hydropower plant (Fish protection and downstream migration)
- Information on diversion channel upstream and downstream regarding the hydropower station (length, depth of the river, width, type of construction, status of construction)

D. Data on existing fish passage facilities

(Information about fish pass next to barrier or hydropower station possible)

- Type of construction
- Length
- Width
- Hydraulic gradient

- Discharge
- Information about assembly parts (number of steps, size, water depth)
- Status of construction
- Functionality with explanation
- Attraction with explanation

E. For the evaluation of sites other maps were prepared and integrated into the data management (GIS):

- River zoning in North Rhine Westfalia for river basins ≥ 20 km^2
- Fish counter
- River for migrating fish
- Nature protection area
- Biotope regarding rivers
- Landscape
- Concepts for natural development (environmental friendly)

QuIS is the central fish migration barrier inventory for North Rhine-Westphalia. The database stores all relevant information from a variety of sources to provide a national decision support. QuIS forms the basis for the ecological evaluation of fresh waters and hydropower potential estimation for barriers in North Rhine-Westphalia, and thus provides a tool to facilitate the implementation of the EU WFD (e.g. used in preparation of reports, management plans, and the development of restoration strategies).

Ecological evaluation of fresh waters considers fish and benthic invertebrates based on the premise that aquatic organisms are directly influenced by their environment, including anthropogenic impacts, and are thus suitable indicators of ecological status. The methodology compares the current observed distribution of aquatic organism with that expected based on historic information and river zone classification systems. River zone classification systems (e.g. Huet, 1959) predict the longitudinal distribution and diversity of species if unaffected by anthropogenic factors. In North Rhine-Westphalia, the diversity of species expected is defined for specific river zones. By assessing distribution of aquatic fauna, the longitudinal connectivity of rivers, and hence the disruption caused by barriers, can to some extent be assessed. The displacement of communities, either due to an inability to pass barriers or a result of impacts on habitat, can be used to illustrate anthropogenic perturbations.

The methodology operates at both the "site" and "catchment" scale. In the latter, the impact is considered from the perspective of the entire river basin affected by barriers, hydropower facilities, and/or water diversion system and extends from the barrier to the estuary. All sites are evaluated based on the longitudinal connectivity and ability of aquatic organisms to move up- and downstream. A component of the assessment involves quantifying the effectiveness of fish passage and screening facilities. The loss of habitat associated with the development of infrastructure for diversion and impoundments is also evaluated. The site assessments are based on five categories, and resulting maps created illustrate status of rivers for which a colour scheme is used to indicate assigned status of the water body.

Barrier porosity for upstream migration is assessed on three components: (a) the permeability / passability of the barrier itself; (b) attraction of the fish pass; and (c) efficiency of the fish pass for enabling upstream movement of fish through it. Upstream migration is only considered feasible when at least one route of passage is available according to the principles described in the manual. For downstream migrating life-stages, passage past barriers is considered feasible if a functioning route of passage is available, and fish are not damaged, e.g. as a result of passage through a hydropower plant. Therefore, at all water diversion and abstraction sites, the following four parameters are examined: (a) ratio of discharged diverted flow to overall flow of the river which can be used to indicate the probability of downstream migrants entering the operational channel or hydropower plant; (b) existence of a route of passage; (c) injury rate associated with barrier passage (e.g., injury associated with passing weir and collision in the tailwater zone); and (d) injury rate associated with passage through a hydropower facility or water diversion system.

Table 2. Assessment criteria for fish pass attraction (translated from Dumont, 2005)

Class	Ecological status for fish	Technical criteria regarding a fish pass for a barrier or water diversion system including hydropower plant with diversion channel	Technical criteria regarding a fish pass for a run-of-river hydropower plant
A	Unimpaired upstream migration of fish.	No barrier exists.	
B	The attraction of the fish pass is not or only slightly impaired: Fish passage facilities must be arranged to guarantee a flawless functioning on at least 300 days per year (cp. DVWK 1996).	Fish pass for a barrier and/or hydropower plant positioned to enhance attraction. Fish passage facilities next to barrier and hydropower plant with diversion channel. The fish pass next to the barrier is easily found under mean flow conditions to enhance passage through the bypass. No dead-end of underwater channel of the hydropower plant **OR** mechanical barrier for fish protection.	The position of the fish passage facility is next to the hydropower plant near the bank of the river: The entrance of the fish pass is not built into the tailwater. The attraction flow is parallel to the main current and is not influenced by alterations of downstream water level. Large and small-scale attraction is ensured.
C	The attraction of the fish pass is moderately impaired: Fish passage facilities must be arranged to guarantee a flawless functioning on at least 240 days per year (cp. DVWK 1996).	Fish pass for a barrier and/or hydropower plant with position which deviates from the guidelines **OR** The attraction is restricted through reduced minimum flow (classification C in Table 9). No dead-end of the underwater channel of the hydropower plant or mechanical barrier for fish protection.	The position of the fish passage facility is next to the hydropower plant near the bank of the river: Position and main current deviates from the state of the technology.
D	The attraction is strongly perturbed through poor position of the entrance of the fish pass.	Fish pass next to the barrier. The entrance is far below, there is no main current which can attract fish **OR** Position of the fish pass similar to the classification B, but minimum flow in diversion channel is similar to classification C in Table 9. Dead-end of the underwater channel is possible.	Fish pass at the bank opposite the hydropower plant. The position is similar to the technical criteria of classification B.
E	The entrance of the fish pass does not attract fish.	The fish passage facility is not attractive because of wrong position of entrance **AND/OR** the minimum flow at the position of the weir/dam is only classification D or E from Table 9.	

Table 3 Porosity assessment criteria for fish passes and barriers (translated from Dumont, 2005)

Class	Ecological status for fish	Technical criteria regarding a fish pass for a barrier	Technical criteria regarding a fish pass
A	Unimpaired Upstream migration of fish	No barrier exists.	
B	The passability of the site is only slightly impaired and possible on at least 300 days per year.	The slope of the barrier is gradual, has a rough surface, and has reasonable water depth (reflects conditions similar to the natural river channel)	Fish pass is state-of-the-art for multiple species / life-stages / and body dimensions.
C	The barrier is passable at least 240 days per year and is impaired for several species and/or sizes.	The barrier is so steep and high that the hydraulic condition limit values are only moderately exceeded, even at higher backwater.	Moderate deviations of limit values for maximal velocity, drop difference and power input.
D	The passability of the site is strongly restricted and only passable for a reduced diversity of species and sizes	The barrier is so steep and high that the hydraulic limit values are strongly exceeded, even at higher backwater.	Deviations of limit values.
E	The site is also not passable by floodwater.	The barrier is not impounded at high water so the hydraulic limit values are exceeded	Strong deviations of limit values.

Table 4 Attraction and porosity criteria for downstream migration through migratory corridor (translated from Dumont, 2005)

Class	Ecological status for fish	Technical criteria regarding a barrier	Technical criteria regarding a fish pass
A	Unimpaired downstream migration of fish.	There is no diversion channel.	No hydropower plant or water diversion system installed.
B	The attraction of migration corridor is only slightly impaired.	Only slight diversion of the water (maximum 25% mean flow MQ), so most of the fish migrating downstream can pass the barrier. The passability of the bypass meets or exceeds the minimum flow according to classification B in Table 9.	The fish passage facility is next to water diversion system according.
C	The attraction of migration corridor is only moderately impaired.	Diversion of the water is up to 50 % mean flow (MQ), so only a small proportion of the fish migrating downstream can pass the barrier. The passability of the bypass is at least as classification C in Table 9.	The position and flow of the fish passage facility next to the water diversion facility deviates moderately from the criteria provided.
D	The attraction of migration corridor is strongly impaired.	Water diversion up to 100 % MQ (mean flow).	The position and flow of the fish passage facility next to the water diversion facility deviates strongly from the criteria provided.
E	No migration corridor exists or attraction is extremely poor	Water diversion over 100 % MQ (mean flow).	No, or no functioning, fish passage facility next to the water diversion system **or** fish pass attraction is extremely poor.

Table 5 Assessment criteria for injury rate associated with barrier passage for downstream migrating fish (translated from Dumont, 2005)

Class	Ecological status for fish	Technical criteria
A	No damage to fish migrating downstream.	No barrier exists.
B	Slight damage to fish migrating downstream.	Drop difference of the barrier less than 10 m **AND** Sufficient water depth in tailwater (at least 25% of the drop difference); no obstacles or other structures, which could damage fish migrating downstream.
C	Moderate damage to fish migrating downstream.	Drop difference of the barrier between 10 m and 15 m **AND/ OR** Insufficient water depth in tailwater (less than 25% of the drop difference) to prevent damage to fish migrating downstream; obstacles or other structures, which lead to moderate damage of fish.
D	Significant damage to fish migrating downstream.	Drop difference of the barrier between 15 m and 20 m **AND/ OR** Insufficient water depth in tailwater (considerably less than 25% of the drop difference) to prevent damage to fish migrating downstream; obstacles or other structures, which lead to major damage of fish.
E	Major damage to fish migrating downstream.	Drop difference of the barrier more than 20 m **AND/ OR** Fish clashes in the tail water against obstacles and other structures.

Table 6 Downstream migration injury rate at hydropower plants and water diversion systems (translated from Dumont, 2005)

Class	Ecological status for fish	Technical criteria for hydropower plants	Technical criteria for water diversion
A	No injury to fish migrating downstream.	No usage of hydropower.	No water diversion.
B	Slight injuries of fish migrating downstream. The population of diadromous and potadromous fish species is not in danger.	Mechanical barrier in front of the hydropower plant with approach velocity of Va ≤ 0.5 m/s and maximum spacing (between bars) dR ≤ 10 mm for anadromous species ≤ 15 mm for catadromous species ≤ 20 mm for potamodromous species[1)] **OR** effective operation management **OR** hydropower usage with slow running waterwheel, hydrodynamic screw or similar turbines with only minor injury(damage) rate of fish	Almost complete return of the diverted water into the river; only slight physico-chemical deviations of the water quality **OR** Mechanical barrier in front of the water diversion system as described in Column 2 of this table.
C	Moderate injuries to fish migrating downstream. The population of diadromous and potadromous fish species is in danger.	Mechanical barrier in front of the hydropower plant including Kaplan and Francis-turbines with large runner diameters and moderate damage rates, approach velocity of Va ≤ 0.7 m/s and dR according to classification B **OR** va ≤ 0,5 m/s and dR ≤ 15 mm for anadromous species ≤ 20 mm for catadromous species ≤ 25 mm for potamodromous species **OR** Moderately effective operation management.	Almost complete return of the diverted water into the river; moderate physico-chemical deviations of the water quality **OR** Mechanical barrier in front of the water diversion system as described in Column 3 of this table.
D	Significant injuries to fish migrating downstream. The population of diadromous and potadromous fish species are in significant danger.	Mechanical barrier in front of the hydropower plant including Kaplan and Francis-turbines with small runner diameters and high damage rates, approach velocity of Va ≤ 1.0 m/s and dR according to classification C **OR** va ≤ 0.7 m/s and dR ≤ 20 mm for anadromous species ≤ 20 mm for catadromous species ≤ 40 mm for potamodromous species **OR** No functioning operation management.	Almost no return of the diverted water into the river; strong physico-chemical deviations of the water quality **OR** Mechanical barrier in front of the water diversion system as described in Column 2 of this table.
E	Extreme injuries to fish migrating downstream. The population of	No effective fish protection in front of the hydropower plant, no existing or functioning operation management **AND**	No return of the diverted water into the river **OR**

	diadromous and potadromous fish species cannot survive.	Hydropower installations with Francis, Propeller, Cross-Flow or Pelton-turbines with extremely high damage rates.	No efficient fish protection installed.

1) For potamodromous species, in which the population is endangered, maximum spacing depends on the specific requirements of these species.

A site will only meet good ecological status if the river upstream and downstream of a barrier remains passable so that population of fish can be sustained. The assessment of barrier porosity is based on the criteria illustrated in Tables 2 - 6. Using this approach, a site's porosity can only be deemed to fit a particular category when all relevant parameters (Table 2-6) meet the criteria stipulated, e.g. to be considered "slightly altered" the site must achieve a classification of B for all criteria.

Overall site classification is based on consideration of assessment values obtained for both upstream and downstream movement, taking the lower classification value for upstream and downstream porosity. Overall evaluation of site porosity is based on the criteria provided in Table 7.

Table 7. Overall evaluation of site porosity.

Class	Upstream	downstream
A	There is no barrier existing.	
B	On at least 300 days per year the fish migrating upstream easily find the migration corridor and move up the river into the headwater.	The fish migrating downstream easily find the migration corridor and move down the river into the tailwater **AND** There is no or only a slight risk of damage when passing the barrier.
C	The attraction and the passability of the migration corridor for individual species is moderately impaired **AND/OR** is attractive and passable on at least 240 days per year.	The attraction and the passability of the migration corridor into the tailwater is moderately impaired **AND/OR** There is a moderate risk of damage when passing the barrier.
D	The attraction and passability of the migration corridor is strongly impaired.	The attraction and passability of the migration corridor into the tailwater are strongly impaired. **AND/OR** There is a strong risk of damage when passing the barrier.

E	The location upstream is not passable.	There is no migration corridor into the tailwater **AND/OR** There is a very strong risk of damage when passing the barrier for fish migrating downstream.

A component of the methodology to evaluate and classify the impact of barriers on ecological status considers the “loss of habitat” (defined as river length) associated with the impoundment of water (e.g. by dams) or through diversions (Table 8 - 10). Evaluation of the “loss of habitat” as a result of diversion considers the ratio of length of diversion channel to length of free flowing channel between the barrier and next impounded section downstream. Evaluation is based on low flow scenarios.

Assessment of ecology status of catchments using this methodology considers the overall impact of all barriers and hydropower facilities. It is not intended to provide a fine-resolution comprehensive assessment of ecology, but does attempt to highlight the influence of limiting factors in relation to the need to achieve "good ecological status". Catchment assessment is based on similar principles to the assessment of individual sites, although it does not distinguish between cause/ purpose of impoundment or diversion. It does attempt to illustrate the overall impact. The impacts of barriers on the catchment are deemed to be “small” if the following requirements are met:

1. **Passability:** To achieve a “good ecological status”, or to improve (support the development of) the ecological potential of the surface water body if heavily modified, fish must be able to pass the barrier at each site in both the up- and downstream directions. It is also important that any impacts on populations of diadromous and potamodromous species downstream of barriers will not adversely affect the sustainability of the population.

2. **“Loss of habitat” due to dams and water diversion:** Based on the definition of “slightly altered”, and hence “good ecological status”, the

maximum acceptable loss of habitat is 25%. Therefore, at least 75% of the length of each river zone must be passable without any barrier. Furthermore, it is desirable that between two successive barriers, at least 75% of the length of the river is passable. The acceptable impact for each river can be found in Table 11 which forms the basis for the evaluation for each site (to obtain a maximum "loss of habitat" of 25%, and hence a "good ecological status").

Table 8 "Loss of habitat" due to impoundment by dams

Class	Ecological status for fish	Technical criteria
A	There is no "loss of habitat" through impounded water.	There is no impounded water.
B	There is only a small portion of "loss of habitat" through impounded water; the majority of the river zone is not negatively affected for rheophilic species.	A maximum of 25% of the river length from weir to the next dam (upstream) or until the connectivity of diversion channel and original river bed is impounded.
C	There is less than 50% "loss of habitat" for rheophilic species through impounded water.	A maximum of 50% of the river length from weir to the next dam (upstream) or until the connectivity of diversion channel and original river bed is impounded.
D	There is more than 50% "loss of habitat" for rheophilic species through impounded water.	More than 50% of the river length from the weir to the next dam (upstream) or the whole of the connectivity between the diversion channel and original river bed is impounded.
E	There is a 100% "loss of habitat" for rheophilic species through impounded water.	The full river length from weir to the next dam (upstream) is impounded.

Table 9 "Loss of habitat" in the original river bed

Class	Ecological status for fish	Technical criteria
A	There is no "loss of habitat" through water diversion.	There is no water diversion.
B	The settlement differs only slightly from those river zones which are not affected by impounded water or water diversion.	Based on a minimum flow value for the diversion
C	The benthic invertebrate fauna only slightly deviates in the diversity of species and abundance from those of the population of unaffected river zones. The relevant species of fish fauna and their developing stages are only moderate damaged.	The minimum flow only depends on the benthic invertebrate fauna
D	The aquatic fauna is significantly impacted and especially specialized species are no longer found in the original river bed.	The minimum flow depends only on the benthic invertebrate fauna
E	The whole biological community is heavily damaged.	There is no, or only little flow in the original river bed when the diversion is equal or smaller than the mean flow (MQ) of the hydropower plant.

Table 10 Impact of "loss of habitat" through water diversion

Class	Ecological status for fish	Technical criteria
A	There is no "loss of habitat" through water diversion.	There is no water diversion.
B	The major part of the river zone is not negatively affected and therefore appropriate for settlement.	A maximum of 25% of the river length from weir to the next dam (upstream) is affected by the water diversion.
C	There is less than 50% "loss of habitat" and therefore at least 50% of the river zone is appropriate for settlement.	A maximum of 50% of the river length from weir to the next dam (upstream) is affected by the water diversion.
D	There is more than 50% "loss of habitat" and therefore there is no unaffected settlement possible.	More than 50% of the river length from weir to the next dam (upstream) is affected by the water diversion.
E	There is a 100% "loss of habitat" for rheophilic species.	The full river length from weir to the next dam (upstream) is affected by the water diversion.

Table 11 Fish-ecological requirement for the river

Ecological effects for fish	Requirements
Upstream migration of fish	The river/water course must be as passable from the origin to the estuary as it was prior to anthropogenic impacts. This ensures that, in particular, anadromous species are able to reach spawning grounds and maintain sustainable populations. It remains an individual decision whether the system of dams can be avoided, especially if only small parts of the river system are isolated (protected). At every site fish passes are state of the art. The site evaluation must achieve classification B.
Downstream migration of fish	At every site, the damage to fish has to be prevented, and downstream migration has to be ensured so that the settlement of diadromous and potamodromous species is not endangered. This status is classification B. The passability of a river system has to be ensured so that the migration of all diadromous species through all barriers and hydropower plants are at most 25% damaged.
"loss of habitat" through dam structures and water diversion systems	In each area of the river basin an unimpaired river area of at least 75% is neither impounded nor impacted by a water diversion system. In addition, the water course between a barrier and the next downstream located dam should be to 75% free-flowing. When the previous condition holds and there is longitudinal connectivity, then a "good ecological status" may be permitted even when the limiting values of an extension of an impounded section and/or the original river bed at the site do not meet classification B.

The barrier information system covers all sites which must be evaluated for their impact on ecological status. Ultimately, this will also provide useful information for decision makers tasked with developing mitigation strategies. Cathment-scale assessments are based on aggregate evaluation of all individual barrier sites within areas ≥ 20 km^2. Evaluations of sites are based primarily on upstream and downstream porosity of fish and benthic invertebrates at each site, and the loss of habitat as a result of non-passable barriers. Loss of habitat is considered in terms of river length.

The methodology has been employed and validated in several regions. Evaluation of the catchment area "Rechtsrheinisches Bergland" (RB) indicated that 32% of barriers were designated as "good" (B) or "impaired" (C) when considered from the perspective of upstream migration. “Impaired” barriers were either impassible for a proportion of the migratory period (temporal component of the evaluation), or for specific species (evaluation criteria “B” and “C”). Of the 370 sites evaluated, 103 had fish passage facilities installed (including 5 fish passes at hydropower plants). Barrier porosity at the remaining sites was dependent on low fall heights (hydraulic head) and dilapidation of the structure.

Evaluation of fish passage facilities at RB considered the effectiveness of 98 structures associated with weirs from the perspective of upstream migration. The percentage of fish passes that were designated to be of “good” status was less than 24%, and those that were considered to provide good attraction represented 24% of the total.

Evaluation of porosity at hydropower facilities at RB indicated that relatively few hydropower facilities provided sufficient fish protection (e.g. screening facilities), an artifact of a lack of consideration of downstream migration when the plants were constructed. Only 14 of 155 hydropower installations evaluated were designated “B” for acceptable injury rate of fish and good attraction through the migration corridors. However, the evaluation process was limited by an inability to acquire sufficient data (e.g., spacing between bars of mechanical screens or in relation to the determination of the approach velocity).

Evaluation of the “loss of habitat” due to impoundment and water diversion in the RB area indicated a significant impact of barriers. In the river Seig, Wupper and Ruhr catchment, an inventory of 1,192 barriers was developed. Assessment indicated that approximately 70% of these sites were not passable, thus preventing “good ecological status” designation. A significant “loss of habitat” as a result of barriers was quantified for this area. For the river Seig, no further action is required in order to meet the criteria for a maximum “loss of habitat” of 25%. However, the 25% threshold was exceeded for the Wupper river basin in the grayling and barbel zones.

It is interesting to note that the methodology employed in North Rhine-Westphalia also combined barrier porosity assessment with evaluation of hydropower potential at the sites surveyed. Hence the development of new hydropower is considered in conjunction with the removal or repair of barriers. The primary factors of interest were the technical (e.g. sufficient hydraulic head and flow) and economic feasibility (where the ratio of expected benefits per year to the total investment costs (return factor k) is > 1:35) of developing hydropower potential of each site. Ultimately, the technical and economic feasibility of developing hydropower potential for the entire catchment is established.

The technical and economical evaluation of each site differed strongly depending on:

- Type of river
- Hydraulic head
- Construction of hydropower plant (Run-of-river or bypass plant)
- Existing buildings and other facilities
- Existing restrictions (such as buildings, land uses and other use)
- Environmental impacts and their resolutions costs

From a catchment-scale perspective, longitudinal connectivity is assessed by considering the cumulative porosity of all sites in the upstream and downstream direction. Cumulative impacts are calculated by multiplying individual barrier porosity scores, following the same methodology as several other assessment protocols previously described.

For most rivers in North Rhine-Westphalia, the connectivity of habitat was considered to be relatively low as a result of the impact of barriers (Dumont, 2005). One of the strengths of the German approach was the facilitation of the construction of maps that depict river classification in line with WFD definitions. From a management perspective such maps can be extremely useful, not only to describe the extent to which barriers impede upstream and downstream migration of individual species based on assessments of barriers porosity, but also to provide a valuable visual description of the magnitude of restoration efforts needed.

The German approach is interesting in relation to the consideration of the temporal component of fish passage, i.e. guidelines provide a general rule that fish passage facilities should guarantee flawless functioning for at least 300 days per year (Dumont, 2006). The exact timings of fish migration are not considered. The strengths of the methodology relate to the considerations of species other than salmonids and both in the upstream and downstream (including for juvenile life-stages) direction. Guidelines for fish passes on which the programme depends are useful and may supplement those already developed by the EA. They are particularly useful with regards to consideration of "nature-like fishways".

In Austria, considerable attention has been directed at the restoration of fluvial connectivity, partly as a result of the requirement to meet the obligations set by the WFD (A. Zitek, Institute of Hydrobiology and Aquatic Ecosystem Management, BOKU, pers. comm.). The Institute of Hydrobiology and Aquatic Ecosystem Management at the University of Natural Resources and Applied Life Sciences in Vienna have recently published a report that describes the approach adopted (Zitek *et al.*, 2007). The methodology is based on a catchment scale approach (e.g. the Danube) and has involved the development of a database of a proportion of barriers to fish migration. It does not, however, reflect a complete fish migration barrier network as not all barriers are reported. Using the inventory developed, efforts made to prioritize barriers for removal or mitigation are based primarily on conservation objectives. Prioritization attempts to meet the requirements of multiple species and life-stages and their ability to migrate in both the upstream and downstream directions. The requirements of species that represent different migratory guilds (long-distance > 300 km, medium-distance 30-300 km, and short-distance < 30 km) are considered in addition to the historic distribution of the species. Prioritization of barriers considers the position of the impediment within the river network; position with regards to the downstream confluence or Austrian border; number of reconnected tributaries; reconnected river length; and position of barriers with regards to Natura2000 (indicating consideration of conservation priorities with regards to fish fauna). It is not clear whether any optimization modelling techniques are employed to calculate the most efficient solution based on cost: benefit analysis. As part of this programme of work, considerable effort has been directed at assessments of fish passage facilities, the passability of which are scored (“fully operative”; “operative”; “limited operative”; “little operative”; “not operative”) (A. Zitek, pers. comm.). Robust scientific assessments, validation, and monitoring of efficiency of connectivity measures have proven to be key components of the approach and should be used as an example of what could be employed in the British Isles. Using information obtained and recorded at the database, decisions are made on whether the barrier may be removed, or suitable provision for fish passage developed. The approach is progressive due to consideration of multiple species and life-stages and migration in both the upstream and downstream direction, although gaps in knowledge related to downstream migration are recognized.

In the British Isles, the EA initiated a programme to develop a National Fish Passage Improvement Prioritisation Methodology (NFPIPM). The initiative aimed to assist local decision making processes; create a nationally consistent means to categorize barriers for fish passage; and identify where National funding bids could better support local area aims. The project recognized the need to develop a national database of all obstructions that have been categorized using a consistent format in order to facilitate prioritization of fish passage projects. In addition to creating a database for several barriers, this initiative also proposed a draft prioritization method based on a multi-criteria analysis. The EA considered comments received from the National Fish Pass Panel and from local area staff and implemented a trialling process. The model was based on each potential barrier being assessed based on the need to improve fish passage to enhance population status of the target species. Thus, there was a need to determine the extent that fish passage was the limiting factor impacting stocks. The method also considered the resulting benefits to the fishery in terms of fish passage improvement and quantity and quality of habitat accessed. The methods also considered how the project will help achieve national and local targets (e.g. in relation to National Fisheries Strategy, biodiversity and recreation drivers, and potentially obligations set by the WFD). The methodology is advanced in that it considered multiple species (salmonids, eels, coarse fish species, and those of high conservation significance). The methodology depends on a creating a priority scoring system based on benefits accrued and in terms of financial gains.

Although the categorization of barrier under this methodology is relatively subjective, and dependent on the opinion of an experienced practitioner, rather than physical and hydraulic measurement relative to fish passage criteria (Ben Wilson, EA, pers. comm.), the basic principles and database development are valid and may be used to form the basis of future development in this area with some modification. The involvement of relevant EA staff to further develop the database component of this methodology in future phases of this project will prove advantageous.

In Scotland, the Scottish Environmental Protection Agency (SEPA) is currently considering the classification of rivers on the basis of fish migration in order to meet WFD classification criteria (i.e., “high”, “good”, “moderate”, “poor”, and “bad”) from a catchment scale perspective. A Technical Advisory Group (UKTAG) report has recently proposed a method by which classification is based on the area (spatial component) of catchment inaccessible to migratory fish during a proportion of the migratory period (temporal component). A "severe loss" of access to habitat is deemed to occur in cases where access to essential habitat is prevented for greater than 80% of the migratory period. Based on this, "high", "good", "moderate", and "poor" status classification can be assigned if severe loss of fish access is less than 1%, 5%, 20%, and 50% of the catchment area, respectively. It is proposed that the classification system be applied to all baseline waters (rivers with catchments > 10 km^2) where barriers are listed and assessed. No severe loss of access is assigned to any barrier where a functional fish pass is in operation. Access is judged to be prevented to the whole catchment upstream from the point of any impassable anthropogenic impediment, while the area of catchment that is naturally inaccessible to migratory fish (e.g. due to the presence of a waterfall) is not included in the overall calculation. Further, catchments are excluded from assessments if ≥ 95% of area is naturally inaccessible to fish, i.e. they are not assigned a low class if the remaining 5% of waters are heavily impacted by the presence of structural impediments to fish movements.

The introduction of the Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR) required that all impoundments that create a head difference greater than 1 m to have been licenced by 1 April 2006. As a result, SEPA maintains a database (SEPA CLAS) and associated spatial GIS information relating to the locations of actively managed impoundments greater than 1m (and also abstraction points). However, applications do not tend to be received for the many redundant structures which continue to pose impediments to fish movement. This data is supplemented by that collected in a project co-ordinated by the Fisheries Research Service (FRS) to record natural and anthropogenic barriers to migration. The FRS project required the Fisheries Trusts to record the presence of barriers to fish migration on 1:50,000 maps that have subsequently been mapped on to a GIS system compatible with that used by SEPA. The point dataset provided by FRS shows the location of barriers and provides code indicating whether barriers are man-made or natural, and whether they are impassable; passable (with a fish pass); or passable (without a fish pass). The database maintains information recorded by the Fisheries Trusts for approximately 80% of Scotland. There are some concerns related to the accuracy of recording of data and subsequent transposition onto the GIS layer (Chris Bromley, SEPA, pers. comm.). Assessment of barrier porosity has tended to focus on the requirements of salmon, and as a result, those designated as passable may not be when non-salmonid species (e.g. eel and lamprey) are considered. FRS are currently continuing to collect barrier data which will be used to update a river classification map that is predicted to be finalized in 2008 (Dominic Habron, SEPA, pers. comm.).

In addition to the initiatives to develop a national database of barriers to fish migration, regional bodies such as the District Salmon Fisheries Boards and

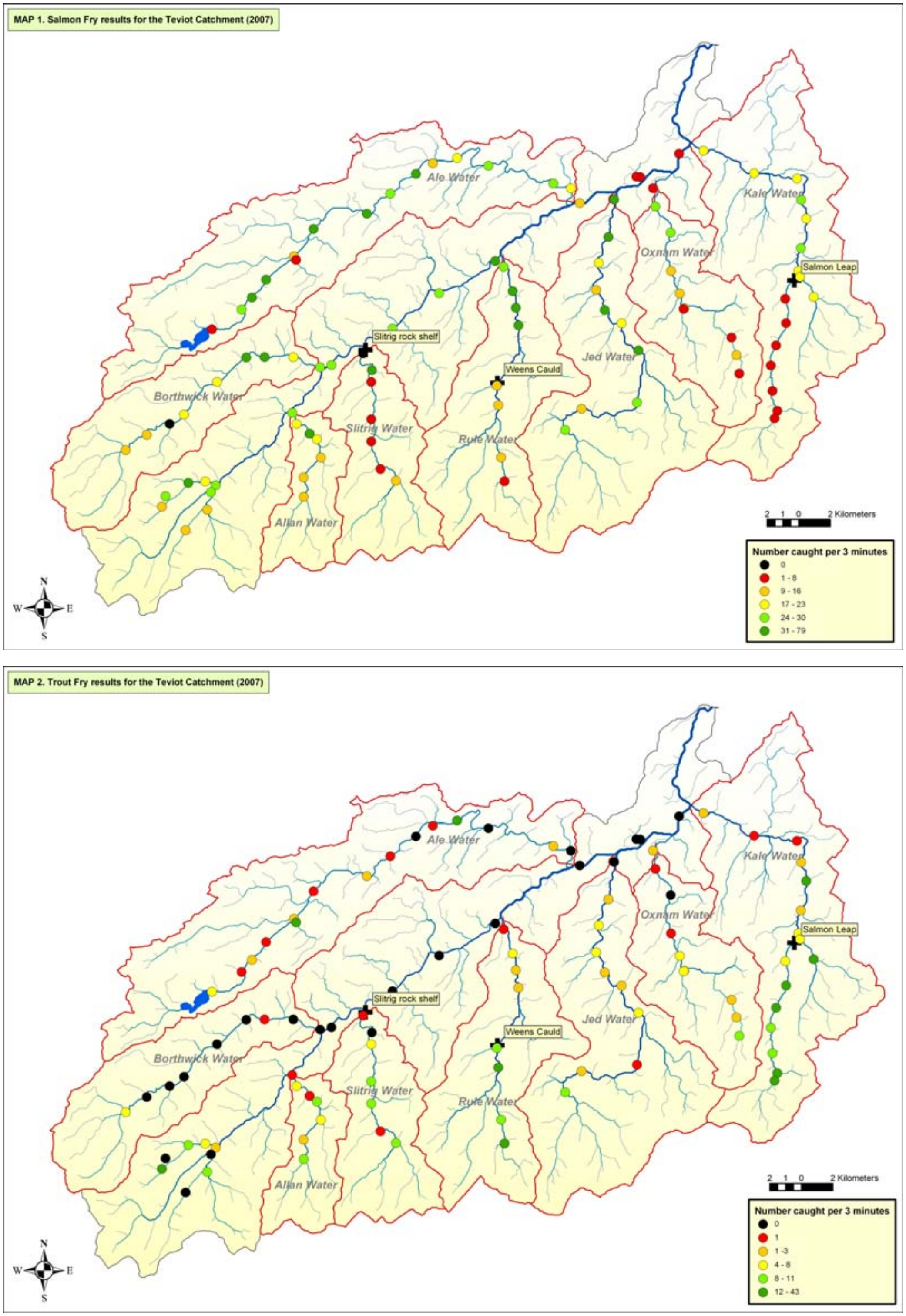

Figure 4 Salmon (map 1) and trout (fry) (map 2) distribution and abundance (based on time spent electrofishing) for the Teviot Catchment 2007. The maps were produced and supplied by Ronald Campbell (Tweed Foundation).

others often maintain detailed information on salmonid distribution (e.g., Fig. 4). This, when considered in conjunction with barrier location information, will provide valuable information for the assessment of the impact of barriers.

SEPA are currently completing the development of a database which describes the morphological alterations to rivers, which includes potential barriers to fish migration (although not assessment of barrier porosity to fish movement). This is known as the Morphology Pressures Database (MPD) and has been developed with the objective of constructing a morphological classification for Scottish rivers and lochs. The database contains detailed location information (x,y coordinates and hydrocoding information to SEPA's Digital River's Network) for a range of engineering pressures on water bodies, including impoundments and culverts (Chris Bromley, pers. comm.).

It is recognized that limited available information on the porosity of barriers to fish migration is a significant factor preventing SEPA from effectively applying new and future powers to mitigate for associated environmental impacts. The need to address this knowledge gap is the principal driver for the current project to develop capability of barrier porosity assessment ultimately to facilitate the prioritization of mitigation strategies. Unlike many methodologies previously developed, the current project requires that anthropogenic and natural barriers that impede the migration of multiple species in both the upstream and downstream directions be considered.

6. HABITAT ASSESSMENT

The recommendation of a protocol for the assessment of habitat in association with quantification of barrier porosity is beyond the remit of this report. Nevertheless, it is necessary to highlight some of the methodologies that are currently used, and the appropriateness of these from the perspective of the British Isles.

Having identified and assigned scores of passability to individual structures, prioritization may be achieved by calculating the costs of mitigation or removal of barriers to migration relative to benefits gained. Benefits are most often considered in terms of measures of habitat gain, i.e., the quantity of habitat accessible after barrier removal or repair, the most simplistic of which quantify river length or area. The WDFW assess potential habitat gain achieved if an individual barrier was corrected by determining whether or not the structure is physically accessible from the downstream direction and whether there is available habitat downstream of the structure suitable for resident salmonids (WDFW, 2000). As with several other habitat assessment protocols, the WDFW methodology is biased to upstream migrating and resident salmonids. The assessments of habitat suitability are relatively coarse, taking into consideration reach length (must be > 200 m), gradient (< 20%), and occurrence of natural barriers. No further habitat assessments take place if initial surveys suggest that there is no access to anadromous salmonids and no availability of suitable habitats for residents. Otherwise, the potential habitat gain for both anadromous and residential salmonids is estimated based on conducting physical habitat surveys in isolation or in conjunction with expanded modelling techniques. Habitat values are usually defined as length (m) of river habitat between each barrier. This metric is simple to use and is that chosen by other agencies, including the Washington State Department of Transportation (WSDOT). However, the SSHEAR database also maintains information from which some other weighted metric (e.g. spawning and rearing habitat) could be derived.

Cost: benefit analysis based on measures of river length or area alone is limited because it does not account for habitat quality. High quality habitat is that which enables individual fish to maximize their fitness, and the availability of which may limit population growth when standing stock approaches the carrying capacity of the environment (Armstrong *et al.*, 2003). Barriers can dramatically impact the proportion of the catchment that is accessible to migratory fish, but also disproportionately impact accessibility to the high quality habitat that is particularly important for specific species and life-stages. For example, barriers that remove small headwater tributary streams from a river network may have a disproportionate impact on potential spawning habitat for some species of salmonid. Steel *et al.* (2004) recognized the limitations of relying on measures of habitat quantity and developed linear mixed landscape models to predict steelhead redd density based on natural landscape patterns such as geology, land-use, and climate variables. These can be used as key indicators of intrinsic habitat potential even in cases where migration is currently blocked by barriers. Based on assessments of steelhead spawning habitat, they found the key physical determinants to be alluvium, gradient (< 6%), landslide-derived geology, young forest, shrub vegetation, agricultural land-use, and volcanic geology. By using the model developed, the authors were able to predict potential redd density upstream of 111 barriers to migration. The technique identified high-priority barriers that might have been overlooked if only stream length was considered. Similarly, Sheer and Steel (2006) quantified and compared habitat quality, land cover, and other physical factors of accessible habitat versus that blocked to migratory fish by barriers, and assessed the impact of barriers on salmonid population status and distribution in the Willamette and lower Columbia River basins. They concluded that prioritization of barriers for mitigation or removal should consider both magnitude and quality of lost habitat, and that simplistic habitat indices such as river length are not sufficient to quantify the impact of barriers.

Assessments of habitat suitability are biased toward species of salmonid. In spite of several decades of research, it remains difficult to define optimal habitat for specific salmonid species and life-stages beyond some broad description of a range of environmental conditions, i.e. to partition variation in habitat suitability into inter-population differences, intra-population preference, intra-population tolerances, and effects of interactions between habitat variables (see Armstrong *et al.*, 2003). It is not surprising, therefore, that definition of habitat suitability or quality is limited for the less intensively studied non-salmonid species (e.g., lamprey and bullhead [*Cottus gobio*]) and life-stages that must now be considered under the directives of European legislation. A lack of understanding of the life history of some species, and how habitat utilization may translate to individual performance and fitness and ultimately population viability, presents a challenge to the development of habitat assessment protocols on which prioritization of barriers for correction may be based. In recognition of these limitations, there may be a pragmatic argument in favour of selecting and concentrating on a limited number of “umbrella” species based on the premise that if barrier removal improves the status of their populations, then other species will likely also benefit (Rory Saunders and Tim Sheehan, pers. comm.). From the perspective of a national programme, it is essential the habitat assessment methodology developed remains consistent between regions and agencies. Further research and development of a suitable methodology is recommended.

7. FISH PASSAGE CRITERIA

7.1 Swimming capabilities

Empirical measures of swimming capability obtained under experimental conditions provide the primary source of information on which fish passage criteria have traditionally been developed. Swimming performance is influenced by species, body length, physiological condition, and water quality factors, primarily temperature (Wardle, 1975; Beamish, 1978; Blake, 1983; Beach, 1984). Based on the pioneering work of Webb (1975) and Beamish (1978), swimming is generally categorized into three modes, commonly referred to as sustained (maintained indefinitely, or for longer than 200 minutes under test conditions); prolonged (maintained for between 15-20 seconds and 200 minutes); and burst or sprint (speed that can be maintained for up to 15-20 seconds). Swim chambers are commonly used to estimate prolonged and burst swimming capability of individual fish. For example, critical velocity (U_{crit}) tests (e.g. Beamish, 1978) are used to estimate the prolonged swimming capability of individual fish maintained at a specific test temperature. Test fish are acclimated to the test temperature prior to the experiment, and then acclimated to the swim chamber at a low velocity (e.g., 10 cm s^{-1}) to enable them to orientate to the flow for a specified period (e.g., 1 hour). After the acclimation period, the water velocity is increased in increments (e.g., 10 cm s^{-1} every 20 minutes) until the fish suffers fatigue and can no longer maintain position against the current and is forced onto a downstream screen. The time at which failure to maintain position occurs is used to calculate the fatigue speed or critical velocity (U_{crit}):

$$U_{crit} = V_p + \left(\frac{t_f}{t_i}\right) V_i$$

Brett (1964)

where,

Vi = the velocity step (cm s^{-1})

Vp = the penultimate velocity reached at fatigue (cm s^{-1})

tf = the time lapsed from the velocity increase to fatigue (s)

ti = the time between velocity increments (s)

Burst swimming (U_{max}) has traditionally been estimated by forcing fish to swim against a set velocity, after a period of acclimation at a low velocity. The highest velocity the fish can maintain position against for up to 15-20 seconds provides U_{max}. In nature, burst swimming is used to enable fish to pass high velocity zones, and requires modulation of the frequency of body and caudal fin undulation (Webb, 1994).

Evaluations of both prolonged and burst swimming capabilities are important when defining fish passage criteria. For example, the potential for fish to pass culverts depends on burst swimming in order to enter and exit the structure, while prolonged swimming may be employed to move through it (Coffman, 2005). This will depend on site specific conditions, as under some flows, fish may be forced to employ burst swimming in order to ascend the entire length.

In cases where hydraulic information is collected during fish migration barrier assessments, it is possible to assign values of passability based on the traditional measures of swimming capability for the target species or life-stage. Several US federal and state agencies have developed predictive models and guidelines to assess passage associated with hydraulic barriers. Many of these are biased towards the upstream movement of adult salmonids at culverts. As a result, they are often inadequate for assessing the fish passage efficiency of other types of structures to multiple species and life-stages. However, there are some models, such as FishXing (Love *et al.*, 1999; Furniss *et al.*, 2006), that do consider multiple species under a variety of flow conditions. Considerable effort may be required, however, to collect the hydraulic data needed to conduct the necessary evaluations.

7.2. Leaping ability

As with swimming performance, the ability of fish to leap over impediments to migration varies with species, body length, physiological status, and water temperature via its influence on muscle effort efficiency. Evaluations of leaping ability have been based on both experimental trials (e.g., Stuart, 1962; Powers and Orsborn, 1985; Holthe *et al.*, 2005) and field observation (Ovidio *et al.*, 2007).

While salmonids are well known for leaping, this capability is much less pronounced or non-existent for many other species. In their assessment of the passability of several weir structures in the Netherland, Winter and Van Densen (2001) assumed that non-salmonid species are unable to leap, and therefore could not transcend free flowing head differences through weirs of 0.25 m.

It is recommended that for the development of a methodology for the British Isles to assess fish migration barrier porosity, a conservative approach is adopted in which salmonids (and grayling to a lesser extent) are considered capable of leaping barriers within the criteria defined (see manual, appendix 1) while other non-salmonid species are deemed incapable of leaping.

7.3. Behaviour

Consideration of fish behaviour is rarely acknowledged during the development of fish passage criteria. Yet behaviour is a critical component of fish migration, and a lack of consideration likely results in the observed lower than expected fish passage efficiencies when validation studies compare realised with predicted values based on swimming and leaping performance. For example, Coffman (2005) observed situations where fish did not transcend culverts that had been classified as passable, possibly due to a lack of motivation to do so.

As a general “rule of thumb”, upstream migrating fish tend to be attracted to areas of highest momentum (flow x velocity) (Powers and Orsborn, 1985). This observation explains why fish passes that provide insufficient “attraction flow” relative to the bulk flow of the river, tend to be relatively inefficient.

Several species of fish have been observed to exhibit behavioural avoidance to a variety of environmental conditions that are associated with structural impediments including abrupt velocity gradients (Haro *et al.*, 1998 for juvenile Atlantic salmon; Kemp *et al.*, 2005a, 2006 for Pacific salmonid smolts) and overhead cover (e.g., Welton *et al.,* 2002 for Atlantic salmon smolts; Moser *et al.,* unpublished data for river herring *Alosa aestivalis* and *A. pseudoharengus*; Kemp *et al.*, 2005b for Chinook salmon [*O. tshawytscha*] smolts). Avoidance behaviour can significantly impact fish passage efficiency and increase delay, potentially elevating the energetic expense of migration and predation risk. It is recommended that members of the assessment team are sufficiently trained and aware of how behavioural impediments may obstruct fish movement at structural barriers and account for this when making subjective evaluations (see manual, appendix 1). However, evaluation of barrier porosity at the data input stage by appropriately qualified personnel may provide the best opportunity to assess the potential for existence of behavioural impediments. For example, the presence of a single culvert may be deemed to have sufficiently limited impact on the downstream migration of salmonids smolts and thus should not be considered a barrier. If, however, an extensive network of culverts are encountered during passage through the migratory corridor, a more detailed empirical evaluation of their impacts may be deemed warranted, especially if the population status of the target species within the specific catchment is considered critical.

7.4. Target species

The target species to be considered as required under the remit of this report were selected by the steering group based on their economic and conservation value from the perspective of the British Isles, and to represent a range of salmonid and non-salmon diadromous and potamodromous species guilds. The target species are Atlantic salmon, brown trout, grayling, eel, river lamprey, sea lamprey, barbel and chub (*Leuciscus cephalus*). Summary details of fish passage criteria for these species are provided in the field assessment guidance manual (appendix 1).

7.5. Caveats to traditional measures of fish passage criteria

Knowledge of swimming and leaping capabilities of migratory fish is necessary if evaluation of their ability to negotiate barriers to movement in the field is to be effective. Unfortunately, while values of sustained, prolonged, and burst swimming performance have been quantified and are now readily accessible for some species (e.g. by accessing models such as FishXing and Swimit), there remain gaps in the data for several other species and particularly over a range of life-stages.

Recent research has questioned the validity of using traditional estimates of swimming capability in assessments of fish passage efficiency. In the majority of cases, measures of sustained, prolonged and burst swimming are based on assessments conducted under conditions in which fish are forced to swim within experimental chambers (e.g., Brett, 1964; Jones *et al.*,1974; Stahlberg and Peckmann, 1987; Videler, 1993; Peake *et al.*, 1997). It may be argued that these measures are misleading because swimming performance is impaired under the highly unnatural conditions where behaviour is restricted to rectilinear swimming. There are few examples of studies in which fish are allowed to volitionally encounter structures with large-scale experimental open-channel flumes that more closely approximate to natural conditions (exceptions include: Colavecchia *et al.*, 1998; Haro *et al.*, 2004; and work currently being conducted at the International Centre for Ecohydraulic Research [ICER] at the University of Southampton). However, fish are able to attain higher swimming speeds in more natural, longer channels (Haro *et al.*, 2004; Peake and Farrell, 2005; Castro-Santos, 2004, 2005) where they are able to utilize alternative behaviours such as “burst-glide” swimming (Tudorache *et al.*, 2007). There is also a lack of information on the burst swimming capability of many species and little data on estimates of sprint distances (maximum distance of ascent) through high-velocity flows (Haro *et al.*, 2004). The lack of information on “true” burst swimming capabilities is significant when defining barrier porosity because assessments may be based on data that significantly underestimates swimming performance of several species. Further, fish may be able to utilize the flow dependent complex and heterogeneous hydraulic conditions and turbulence encountered in nature, during forward and upward movements. For example, Haro *et al.* (2004) observed that upstream migrating fish were able to utilize a hydraulic jump created under supercritical flow conditions to ascend an experimental flume. In a field study, Ovidio *et al.* (2007) found that brown trout were capable of leaping structures of greater height than the theoretical leaping capacity of the species (Beach, 1984). Conversely, fish may be less capable of accommodating complex hydraulic conditions (Hinch and Rand, 2000; Webb, 1998) and thus a reduction in swimming performance is observed despite mean velocity values being within the range deemed suitable for fish passage. These factors are not accounted for under simplistic swim chamber tests and thus the influence of complex hydraulics can not be easily determined using theoretical curves of swimming and leaping performance alone. Instead, the capability of fish to negotiate structural impediments and associated hydraulics require further verification in the field (e.g., Ovidio *et al.*, 2007).

It appears that the behavioural component of performance is significant and must be considered to better understand its influence on swimming capabilities. There currently exists an almost complete lack of understanding of how the behavioural component of volitional swimming influences performance under complex fluid flows that are common in nature, especially in relation to less commonly studied non-salmonid fishes.

Assessments of barrier porosity tend to consider each structure independently of others relative the locomotory performance of the target species. That is, the cumulative impact of passing several barriers on swimming performance is not generally accounted for. Fish may experience fatigue in association with barrage passage that may impact their overall performance capability. If fish employ burst swimming to pass high velocity zones, then it is important to consider their ability to recover prior to performing further bouts. Recovery after exhaustive swimming varies with species (Black et al, 1962; Milligan and Wood 1987, Nelson 1990, Boutilier *et al.* 1993, Keiffer, 2000), and in some is frequently linked to high levels of mortality (e.g., Wood *et al.* 1983). Conversely, fish passage efficiency may increase with time, possibly reflecting an increase in swimming capability as a result of growing larger, or because some factor associated with experience (learning or a “training” effect) proves advantageous.

8. TYPES OF PHYSICAL BARRIER

8.1. Culverts

Culverts are closed conduits commonly engineered to divert stream channels at road or railway crossings. Fish movement through culverts can be significantly lower than through other road-stream crossing structures (Warren and Pardew, 1998), thus impacting natural dispersal rates and increasing habitat fragmentation (Utzinger *et al.*, 1998; Warren and Pardew, 1998; and Trombulak and Frissell, 2000). As a result, fish species abundance (Whitney and Bailey,

1959) and diversity (Barton, 1977) are negatively impacted, and ultimately local populations can become extinct (Fahrig and Merriam, 1994), e.g., as a result of genetic isolation (Kershner *et al.*, 1997).

Culverts can create jump, velocity, depth, exhaustion and behavioural barriers (Coffman, 2005). The upstream migration of salmonids is influenced by channel slope (Adams *et al.*, 2000), pipe slope (Belford and Gould, 1989), and water velocity (Slatick, 1971; Belford and Gould, 1989). Culverts impede upstream movements if water velocities exceed swimming capabilities, or depth is insufficient to enable passage. Culverts may also block fish migration if they create areas of excessive turbulence, are blocked by debris or sediment, or if the outflow is perched as a result of downward erosion by plunging flow (WDFW, 2003).

In recognition of negative impacts of culverts on fish migration, considerable effort has be directed at improving the design of culverts so that they are more “fish friendly”, e.g. by the placement of weirs and baffles within the culvert barrel (e.g., Rajaratnam *et al.*, 1990; Ead *et al.*, 2002), resulting in several guidance manuals that illustrate suitable design criteria (e.g., CDFG, 2002; NMFS, 2001; ODFW, 2004; USDOT, 2007). Many barrier assessment protocols also tend to concentrate primarily on culverts (e.g., Clarkin *et al.*, 2003; Coffman, 2005; Taylor and Love, 2003). It may be argued, however, that the majority of design manuals are not user friendly due to the requirement for extensive technical detail. This, in part reflects the wide variety of culvert shapes and designs (e.g., round, oval or elliptical, and squashed pipes, open bottomed arches or boxes) and the differing hydraulics associated with them. For example, Coffman (2005) found that circular culverts constrict the flow of water causing increased velocity and downstream scouring, and produced the highest water velocity second only to a bedrock chute. It has also been recognized that the development of these protocols and guidelines are biased towards anadromous Pacific salmonids, while consideration of the passage of resident stream fish assemblages has been limited (Coffman, 2005).

The US National Marine Fisheries Service - Southwest Region developed guidelines for the design of stream crossing to aid the movements of upstream and downstream migration salmonids (NMFS, 2001). The guidelines state that the following alternative road-crossing features should be considered in order of preference:

1. Nothing – Road realignment to avoid crossing the stream.
2. Bridge – spanning the stream to allow for long term dynamic channel stability.
3. streambed simulation strategies – bottomless arch, embedded culvert design, or ford.
4. Non-embedded culvert – this is often referred to as a hydraulic design, associated with more traditional culvert design approaches limited to low slopes for fish passage.
5. Baffled culvert, or structure designed with a fishway – for steeper slopes.

The NMFS (2001) guidance manual describes three design methodologies for culverts taking into consideration the need for adequate fish passage: active channel design; stream simulation design; and hydraulic design. The active channel design focuses on using large (minimum culvert width ≥ 1.5 times active channel width) and deeply embedded (culvert bottom buried to depth > 20% culvert height at outlet, and < 40% of culvert height at inlet) culverts so that natural channel dynamics can take place unhindered within. The stream hydraulic conditions within such culverts are intended to mimic natural stream conditions. This methodology is suitable only for relatively low gradient slopes (< 3%) and if culvert lengths are less than 30 m.

The stream design methodology requires a greater level of engineering expertise based on hydrological and geomorphological information than the active channel design method (NMFS, 2001). The objective is to recreate natural stream processes (fish passage, sediment transport, and flood and debris conveyance) within the culvert. Culvert width criteria are defined based on bankfull channel width (minimum culvert width ≥ bankful width and > 1.8 m) (NMFS, 2001). The culvert slope should be equivalent to the slope of the natural channel and should not exceed 6%, and the culvert bottom should be buried between 30% and 50% of the culvert height (NMFS, 2001). The bed sediment should be similar to that of the adjacent upstream and downstream channel.

Culverts based on the hydraulic design method should present suitable hydraulic conditions to enable fish passage on the premise that velocities do not

Table 12. Culvert Guidance criteria illustrating maximum velocities permitted in through culvert barrel to enable upstream migration of adults salmonids (adapted from NMFS, 2001).

Culvert length (m)	Velocity (m/s) – Adult salmonids
< 18	1.8
18-30	1.5
30-61	1.2
61-91	0.9
> 91	0.6

exceed the swimming capabilities of the target species and life-stage (NMFS, 2001). As a result of this, the principles of design are relatively narrow focused, considering only a few species of fish (salmonids) rather than ecological processes (e.g., River Continuum Concept, Vannnote *et al.*, 1980). In recognition of inaccuracies associated with both measures of hydrology and fish swimming capabilities, design assumptions tend to be relatively conservative (NMFS, 2001). Basic data requirements include high (maximum water velocity within the culvert; e.g., 1% and 10% annual exceedance flow for upstream migrating adult and juvenile salmonids respectively) and low (minimum depth within the culvert; e.g., 50% and 95% annual exceedance flow for adults and juveniles respectively) fish passage design flows and information on fish swimming capabilities, and water velocity and depth measurements to enable hydrological and hydraulic analysis (NMFS, 2001). The design criteria based on this method require a minimum culvert diameter ≥ 0.9 m; slope ≤ stream slope, and not greater than 0.5% if embedded. It is advisable to embed the culvert to a minimum of 20% of height below the tailwater control point (NMFS, 2001).

Using the hydraulic design method, the maximum average water velocities in the culvert at high fish passage design flow should not exceed 0.3 m s^{-1} for upstream migrating juvenile salmonids, independent of culvert length (NMFS, 2001). NMFS (2001) provide guidance criteria (Table 12) based on culvert length for maximum velocities for upstream migrating adult salmonids. The minimum water depth at the low fish passage design flow is 0.3 m and 0.15 m for upstream migrating adults and juvenile salmonids respectively. If a hydraulic drop is unavoidable it should not exceed 0.3 m and 0.15 for adults and juveniles salmonids, respectively. If the culvert outfall is perched, a plunge pool should be present that exceeds 0.6 m depth (NMFS, 2001).

The barrier assessment protocol developed by Coffman (2005) builds on the previous culvert design guidelines because it considered multiple species (guilds based on morphology and modes of swimming). Coffman (2005) suggested that the following culvert characteristics contributed to the creation of a barrier to upstream movement:

- Outlet drop and outlet perch (jump barrier)
- Culvert slope (velocity barrier)
- Culvert slope x length (exhaustion barrier)
- Presence of natural stream substrate in culvert (depth barrier)
- Relationship of tailwater control elevation to culvert inlet elevation (depth and velocity barrier).

Coffman (2005) found that fish movement through culverts was negatively correlated with culvert slope, slope x length, and velocity for cyprinids. Road crossing with outlet drops < 10 cm, slope < 2.0%, and slope x length values < 25 experienced the greatest movement illustrating the importance of those culvert characteristics in determining fish passage. Based on the consideration of multiple species / guilds, it is suggested that the Coffman (2005) methodology may form a valid template on which a British Isles methodology may be developed in the future. However, the initial methodology defines assessment criteria based on guidelines developed by Scottish Executive and the Environment Agency (see guidance manual, appendix 1).

It is important to consider the temporal component of fish passage efficiency when considering the impact of culverts. Culverts often form barriers to fish movements under specific low or high flow conditions. Therefore, assessments may be required over a range of flows to estimate the porosity of the structure to fish movements.

8.2 Weirs

Weirs are used for a multitude of purposes, e.g., to regulate water levels, stabilise channels, and to create a head difference e.g. for hydropower generation, or to create critical flow (e.g., for gauging purposes). Single or a series of overshot weirs are relatively common. Fish passage is influenced by a multitude of factors, including the number of steps, height of the steps, and plunge pool depths.

8.2.1 Non-gauging weirs

Non-gauging weirs are most commonly used to regulate and stabilise water levels. Non-gauging weirs are used to create a head difference, e.g. for milling purposes, or hydropower generation, and may be categorized as vertical, sloping, or stepped (G. Armstrong pers. comm.).

Fish passage efficiency is influenced by a number of factors including weir type, number of steps, height of the steps, plunge pool depths, flow conditions (whether the weir is drowned and whether water is "plunging" or "streaming"), and presence of an adherent or non-adherent nappe of flow (G. Armstrong Pers.

Comm). Stepped weirs are particularly problematic for fish passage, unless the weir is drowned under high flow conditions.

Based on Larinier (2002) descriptions of pool and weir fish passes, the critical parameters that influence fish passage efficiency of vertical weirs is the shape, dimension, and heights of the weirs and associated notches and slots. Fish passage is easier the smaller the head difference (DH) between the upstream and downstream water levels. The maximum velocity of flow created by the head difference can be approximated by:

$$V = (2g\ DH)^{0.5}$$

where g is the acceleration due to gravity (9.81 m/s^2).

For example, head differences of 0.15 m, 0.30 m, and 0.45 m correspond to approximate maximum flow velocities of 1.7 m s^{-1}, 2.4 m s^{-1}, and 3.0 m s^{-1} respectively (Larinier, 2002). Therefore, the ability of fish to negotiate vertical weirs depends largely on the swimming and leaping capabilities. In cases where the flow of water is "plunging", i.e. because the downstream water level is below the weir crest causing the nappe of water to plunge towards the floor of the downstream pool, then a head difference of 0.30 m is preferable for salmonid passage (although this may be as high as 0.60 m for the larger salmon and sea trout, or 0.45 m for trout) (Larinier, 2002). Note that the committee on Fish Passes (1942) recommended that the drop in water levels between pools in pool and weir fish passes should not exceed 0.45 m (Scottish Office, 1995). For non-salmonid species, Winter and Van Densen (2001) assumed that they are unable to leap and could not pass free flowing head differences through weirs of 0.25 m.

Under conditions of plunging flow, the depth of water below a vertical weir should be sufficient to enable leaping in salmonids and to ensure efficient dissipation of energy, thus reducing turbulence. The Committee on Fish Passes (1942) criteria for pool and weir fish passes suggests that depth of the downstream pool should not be less that 1.2 m (Scottish Office, 1995).

Fish passage is enhanced when water flows over the face of the vertical weir to form an "adherent nappe" rather than a free flowing jet (non-adherent nappe) because fish can use this film of water to progress up the weir (Stuart, 1962).

Under "streaming" flow conditions, where the downstream water level is 0.5 - 0.6 times the upstream level above the crest of the weir, the main flow of water remains at the surface. Under these conditions, the head difference should preferably remain between 0.30 - 0.40 m for salmon and sea trout, < 0.30 m for trout and fast-water cyprinids such as barbel, and between 0.15 m - 0.25 m for other cyprinids (Larinier, 2002).

Sloping weirs can impede the movement of migratory fish as result of the shallow depth and velocities of water flowing over the downstream face of the weir, and potential presence of a hydraulic jump. The hydraulic jump can in some instances facilitate fish passage (e.g. submerged waves at vertical barriers); have no significant impact (e.g. undular wave); or form a barrier (e.g. free standing waves) (Stuart, 1962). Key determinants in fish passage efficiency are length and gradient of the downstream face, discharge (influencing velocity and depth, Beach 1984), and presence of fish passage structure, such as a diagonal baulk. A diagonal baulk fish pass is usually a rectangular wooden or concrete structure that creates a channel as it runs at an angle across the face of the weir from the crest to the toe. Sloping weirs that might otherwise be passable to migratory fish may create impediments to movement if they have any form of "lip" at the crest. More information relating to the fish passage efficiency of sloping weirs is provided in the section on Crump weirs below.

Stepped weirs can pose significant barriers to fish movement, especially under low flow conditions when water depth of the structures is insufficient to enable both swimming and leaping. Stepped weirs become passable if drowned.

8.2.2 Gauging weirs

Gauging weirs are overflow structures usually extending the width of the channel which are used to accurately measure the rate of flow of the water (Aisenbrey *et al.*, 1978). The ability of fish to ascend gauging weirs is mainly determined by the required swimming speeds and endurance to counter the flow (Turnpenny *et al.*, 1999). Gauging weirs accelerate the flow in order to accurately estimate flow conditions within a waterway. This acceleration of flow, combined with the reduced depth as water passes over the weir create difficult conditions for fish ascent. Turnpenny *et al.* (1999) summarized the characteristics which can cause a weir to act as a barrier to migration:

- Weir type.
- Weir height (varies according to flow).
- Slope of the downstream face – affects velocity and the thickness of the water sheet for fish to swim through.
- Roughness of the downstream face – smooth faces are less easily ascended by fish than roughened surfaces that dissipate energy and decrease the overall velocity, also creating a boundary layer through which smaller individuals may swim.
- Hydraulic conditions in the downstream pool – leaping species require deep water below a weir to gain momentum before leaping. Noise associated with the hydraulic jump created at the transition point may attract fish and initiate leaping behaviour. Excessive turbulence, however, can make it difficult for fish to pass. The approach velocity at the tail of the pool must be low enough for fish to negotiate. Sufficient depth at the approach can achieve the required velocity. The prolonged, rather than burst, swimming speed of the fish should be considered when considering flow velocities in the downstream pool, as it will otherwise limit the ability of the fish to ascend the slope.

- The discharge – this affects the water velocity, the head difference the fish must negotiate, and the thickness of the water sheet. Therefore, passability varies according to flow.

Simple overshot and undershot gauging weirs possess similar characteristics as for overshot and undershot sluices. However, there are a number of other types of weirs used for gauging and/or regulating river flows which are described below.

8.2.2.1 Standard Crump weir

A Crump weir is a two dimensional, triangular profile weir (see manual appendix 1). It has a standardised shape with the upstream edge having a 1:2 sloping face, which causes an increase in velocity due to the reduction in available cross-sectional area. The downstream slope is 1:5. The depth of water decreases as it accelerates over the downstream face. The flow and velocity in this region is termed "super-critical". The rapid return of this super-critical flow can cause a hydraulic jump which can cause significant erosion. Therefore a stilling basin is often used to dissipate turbulence.

Crump weirs can present a barrier to fish movement due to the shallow depths and high velocities of water flowing over the downstream face; the length of the weir face; and the inability of the fish to overcome the hydraulic jump. Trout (266 mm fork length) were found to be capable of crossing slopes of at least 26% and 2.98 m in length at a minimum water temperature of 7.7ºC and of 16.5% and 5.13m in length at 8.5ºC (Ovidio *et al.*, 2007). Grayling (300 mm fork length) crossed at least slopes of 12% and 6.21 m in length at a temperature of 10.1ºC. Trout and grayling cleared slopes of 10% over 8 m after having jumped a 0.59 m crest (Ovidio *et al.*, 2007).

The presence of a stilling basin can dissipate energy and reduce the negative effects of the hydraulic jump and turbulence, making it easier for fish to approach the obstacle. Beach (1984) describes the conditions required for salmonids to pass Crump weirs and this could be used as a basis for defining salmonid passage criteria. However, even powerful swimming salmonids species have difficulty coping with large Crump weirs. They can become disorientated when they leap onto the downstream face and are easily washed back downstream. Weaker swimming species will have considerably greater difficulty passing Crump weirs. It may be easier for fish to pass a Crump weir when it is completely flooded as the distance over which the fish will be challenged will be reduced (Armstrong *et al.*, 2004). Fish passage will also be influenced by the material from which the weir face is constructed. A smooth surface tends to be more difficult to pass than a rough surface. Some Crump weirs are modified, e.g. with baffles, in order to facilitate fish passage.

8.2.2.2 Compound Crump weir

A compound Crump weir (see manual appendix 1) is similar to a Crump weir but has two or more adjacent Crump weirs each of a different height. Compound Crump weirs are employed in watercourses where there is a high variability in flows. In addition to the lower section allowing for operation of the gauging weir under lower flows, it provides an easier route for fish passage (Beach, 1984).

8.2.2.3 Essex weir

An Essex weir is a single Crump weir with an angled, sloping triangular profile flanking the crest of the weir (appendix 1). This structure has improved flow measurement capabilities at low flows.

8.2.2.4 Flat-V weir

The flat-v weir (appendix 1) provides sensitivity at low flows without the need of an extra weir (as with a compound Crump) (Beach, 1984). Two cross-sectional profiles are common 1:2/1:2 and 1:2/1:5 (as with a Crump weir), with traverse slopes of between 1:10 and 1:40 (Beach, 1984; Turnpenny *et al.*, 1999).

Problems encountered by fish are similar to those of the Crump weir. At low flows, however, water is contained at the centre of the weir where fish encounter high velocities. Fish can be disoriented at the sides of the weir due to the formation of vortices. However, the greater depths at the centre of the weir provide conditions that allow fish to create greater thrust and thus pass more easily.

8.2.2.5 Broad crested weir

A broad-crested weir is a general description for a raised overflow crest (Turnpenny *et al.*, 1999), with crests that are significantly larger than sharp crested weirs and have a higher capacity for high discharge. Due to the greater discharge handling capacity, broad crested weirs are generally used for flow measurements in large rivers (Hamill, 2001). Although still in use, these structures are now rarely installed due to a low accuracy of gauging performance and the vulnerability of their upstream edge to damage, which affects the calibration and accuracy (Beach, 1984).

8.2.2.6. Sharp crested/ plate weir

Sharp crested weirs (or notch weirs) are used to measure discharge in small channels where accuracy is required (Hamill, 2001). They have a sharp edge at the crest, causing the water to flow clear of it (appendix 1). This jump is necessary for accurate flow measurements to be made. The flow characteristics of sharp crested and plate weirs are similar. The overflow section of plate weirs tends to span the entire width of the channel compared to the constricted flow of sharp crested v-notch and rectangular notch weirs. The nature of the flow of water over the top of the weir causes difficulties for fish passage. These difficulties are similar to those created by overshot sluices described later.

Sharp crested weirs are usually made of sheet brass or stainless steal with a notch cut out into the plate. A notchless sharp crested weir consists of a simple flat plate. Notches allow for measurements to be accurately taken under a variety of flow conditions. Fish passage will be problematic unless the weir is flooded or there is a minimal head difference between the upstream and downstream sides.

8.2.2.7 Flume weir

Flume weirs are employed in small open channels and are successful at gauging under relatively large discharge conditions (Hamill, 2001). A flume weir is a width constriction where an acceleration of flow occurs through the narrowed channel (appendix 1).

Fish passage success will most likely be affected by the width at the narrowest point of the flume (influenced by the behavioural response of fish), the length of the area where there is increased flow (endurance of fish), the water velocity (swimming speed of fish), and the behavioural response of the fish to the hydraulic conditions associated with the flume.

8.2.2.8 Compound weir

A compound weir combines two or more weir types. Secondary weirs can be located adjacent to the principal weir, as with the compound Crump weir, or it is positioned immediately downstream. The presence of the secondary weir usually allows accurate measurements during low flows and more readily accommodates fish passage (Turnpenny *et al.*, 1999).

8.3. Sluices

Sluices are relatively common adjustable structures used to regulate water flow, often in narrow river and canal systems. A gate can be raised or lowered to allow water to flow through the structure. Beach (1984) identified three main categories of sluice: undershot, overshot (or overspill), and radial.

8.3.1. Undershot sluices

Undershot sluices (appendix 1) regulate flow by allowing water to pass underneath the sluice gate. An undershot sluice can be difficult for fish to pass due to the requirements for high burst speeds and long periods of endurance swimming. This is because the sluice commonly has a base block that causes a water jet to form, while a flat concrete base causes the high velocity flow to persist over a considerable distance (up to the hydraulic jump) (Beach, 1984). Alternatively, sluices that are configured to have a graded approach to the stilling basin, and where a base block is absent, tend to have higher fish passage efficiencies. In such cases, high water velocities are rapidly dissipated, and the hydraulic jump occurs closer to the sluice gate (see appendix 1).

Large sluice gates which are raised only a few centimetres produce flow conditions which may be attractive to fish but impassable. For fish passage a minimum aperture of 30 cm x 30 cm is considered necessary. It is better to regulate flow through a number of adjacent sluice gates rather than through a single large one. Highly turbulent water and high velocities can damage or even kill small downstream migrating fish (Baumgartner *et al.*, 2006). Therefore minimal turbulence and velocities are necessary to allow upstream migration and to permit safe downstream migration at undershot weirs.

8.3.2. Overshot sluices

Overshot sluices regulate flow by allowing water to flow over the sluice gate (appendix 1). Overshot sluices with a sharp upper edge can produce a jet of streaming water over the sluice gate which, in conjunction with shallow depths on the downstream side, may provide inadequate distance for upstream migrating leaping species to negotiate the structure. Downstream migrating species and life stages may be adversely impacted, due to mechanical damage associated with impact on downstream structures or substrate. Stress may also be induced by increased turbulence. Fish passage efficiencies are high if the upper edge is curved, resulting in a shorter and smoother jump of water flowing over the crest of the sluice gate. The movement of fish over the sluice is made easier as the water adheres more closely to the sluice gate edge.

The presence of a downstream stilling basin, if sufficiently deep, can enhance the approach conditions so that leaping species are better able to negotiate the structure. The stilling basin can also reduce hydraulic stresses imposed on downstream migrating fish passing over the sluice gate. Although, the presence of a stilling basin downstream of the sluice gate is important, the depth of any plunge pool in the absence of a stilling basin is significant determinant of fish passage efficiency for leaping species.

As with undershot sluices, fish passage is facilitated if there are a number of adjacent narrow sluices present instead of one large gate, while still maintaining controlled regulated flow function of the weir. Overshot sluices will only be passable by leaping species, e.g. Atlantic salmon and sea trout, unless there is minimal head difference between the downstream and upstream sides.

8.3.3. Radial sluices

Radial type sluices (appendix 1) are virtually impassable to fish. Only when the gate is under flood conditions, so that the downstream side is deeper than the base of the gate, will it be lifted so that fish can pass.

8.4. Dams

A dam may be defined as any anthropogenic structure that results in an abrupt change in water elevation (WDFW, 2000). In fact, natural obstructions such as debris or beaver dams may, in some cases, also impede the movement of fish. Small structures, e.g. weirs, that become inundated or free-flowing during high discharge events, provide at least some limited opportunities for upstream fish passage. Conversely, large dams constructed for the purpose of impounding water for hydropower generation or water supply, pose a complete obstruction for all upstream-migrating fish if bypass systems are unavailable. Assessments of fish passage efficiency at large dams tend to rely on fish count data (e.g. counters may be positioned within adult fish ladders), or detailed assessments using radio or PIT telemetry. However, even though large structures may represent significant barriers to fish migration, they are often excluded from considerations of barrier assessment and prioritization methodologies as they are considered essentially permanent structures, the removal of which involves considering a host of competing social, political, and economic concerns in addition to environmental considerations (O'Hanley and Tomberlin, 2005). Nevertheless, for assessment and prioritization methodologies to be effective, information relating to the entire fish passage barrier network is required, including that for large dams. Rapid assessments of these structures are not straight forward and will depend on additional information including fish counts, distribution of populations upstream and downstream of the structure; and the results of fine-resolution telemetry studies.

In Scotland, the introduction of the Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR) may result in greater requirement for fine-resolution assessments of fish passage efficiency as part of the relicencing process. Detailed assessments of fish passage efficiency for multiple species migrating in the upstream and downstream directions can be achieved using telemetry techniques in conjunction with computational fluid dynamics (CFD) modelling.

8.5 Fords and bridge / aquaduct footings

Fords are permanent crossing places for vehicles or machinery (Environment Agency, 2003). They can range from large structures that impound upstream water creating a head difference, and act as an impassable dam, to small river crossings with virtually no man made material within them. Under low flow conditions, fords can be barriers to fish passage due to insufficient depth for fish to traverse the obstruction. Some fords are vented and have a culvert passing underneath in order to facilitate fish passage.

The river habitat survey (Environment Agency, 2003) classifies fords as major, intermediate, or minor. Minor fords are shallow crossings with no artificial bank or river bed material, causing minimal ponding effects. Intermediate fords are shallow crossings with banks composed of artificial material, but bed is natural, and a slight ponding effect may occur upstream, but this is unlikely to affect fish passage. Major fords are potential barriers to fish passage. These are crossing places where both the banks and bed are made from artificial material (e.g., rubble infill or concrete/ tarmac). They cause significant impounding of upstream water.

Bridges or aquaducts, although generally considered to have minimal impact on fish passage, can block migration if constructed on a concrete apron with an abrupt overhang that will prevent upstream movement of non-leaping fish. Under low flow conditions, the depth of water flowing over a level concrete apron may also be insufficient to enable fish passage.

8.6. Fish passage facilities

A fish pass, often also referred to as a bypass or fishway, is an engineered structure that enables fish to negotiate either an anthropogenic or natural impediment to their movement. In the British Isles, legislation requires the provision of fish passage facilities at many in-river structures (Armstrong *et al*., 2004). However, fish passes often do not work if poorly designed, sited, and / or maintained, and thus themselves present barriers to fish migration. Several fish passage design guidelines are currently available (e.g. Environment Agency Fish Pass Manual).

8.7. Natural barriers

Evaluating natural barriers to migration, such as waterfalls, is necessary in order to assess whether the removal or mitigation of anthropogenic barrier upstream represent valid restoration options. When considering upstream migrations, if fish can not pass a natural barrier then they can not be affected upstream of it. Information relating to a complete fish migration barrier network that includes natural barriers will facilitate efficient prioritization of restoration efforts.

8.7.1. Waterfalls and rapids

Waterfalls can potential act as barriers in the same way as dams and weirs. Rapids can provide velocity and turbulence barriers, and have been known to impede the upstream migration of fish for many decades (e.g., Ricker, 1947). Fish passage efficiency through rapids depends on rapid length, and water velocity and depth through the rapids.

8.7.2 Debris dams

Debris dams are natural dams formed from wood moving through the river channel. Whether large debris dams impede migratory adult and juvenile salmonids remains a matter of debate. Some argue that a "balanced approach" to river management is required during which woody structure should be removed if it blocks fish passage, but left if habitat quality is improved (Hendry *et al.*, 2003). Debris dams are usually temporary features that are either moved by man, or are washed out during spates or floods. However, in less dynamic systems, and/ or if the dam is formed around a permanent feature (e.g. a growing tree), then a single structure may remain in place for several decades.

8.8 Abstraction off-takes

Points of river water abstraction (e.g., for domestic supply, hydropower generation, industry, agriculture and other uses) can impede or block the upstream and downstream movement of fish either by limiting the flow through the natural channel or by attracting fish to the off-take route. In addition, structures that impede fish movement, e.g. weirs, are often associated with abstraction points as a mechanism for impoundment or diversion of flow. If the abstraction points are screened, impingement or mechanical damage (e.g., descaling) can negatively impact downstream migrating fish. Fish will potentially enter unscreened off-takes and suffer elevated risk of mortality or damage associated with passing through turbines (at hydropower facilities) or irrigation systems, which if not reconnected to the river downstream will result in 100% loss from the system.

9. RECOMMENDATIONS FOR A BARRIER ASSESSMENT, INVENTORY, AND PRIORITIZATION METHODOLOGY FOR THE BRITISH ISLES.

It is recommended that the methodology adopted is based on information transfer between three component stages: assessment of barrier porosity; inventory of barriers; and prioritization (Fig. 5). It is important that the three components are developed in an integrated manner and not considered as separate parts. As indicated in the review, there are several precedents for assessments of barriers to fish migration, primarily developed in the United States for the upstream movement of adult salmonids through culverts. There are also several examples where data on barrier porosity has been collected by a co-ordinating agency and used to construct a central inventory. It is recommended that current barrier assessment and inventory methodologies are modified and adapted to the requirements of the British Isles in an effort to minimize duplication of effort. In many cases, prioritization techniques are in the early stages of development. It is this final component of the overall methodology that presents an opportunity to develop novel problem solving models that will enable decision makers to develop the most cost-effective strategies to remove or mitigate barriers.

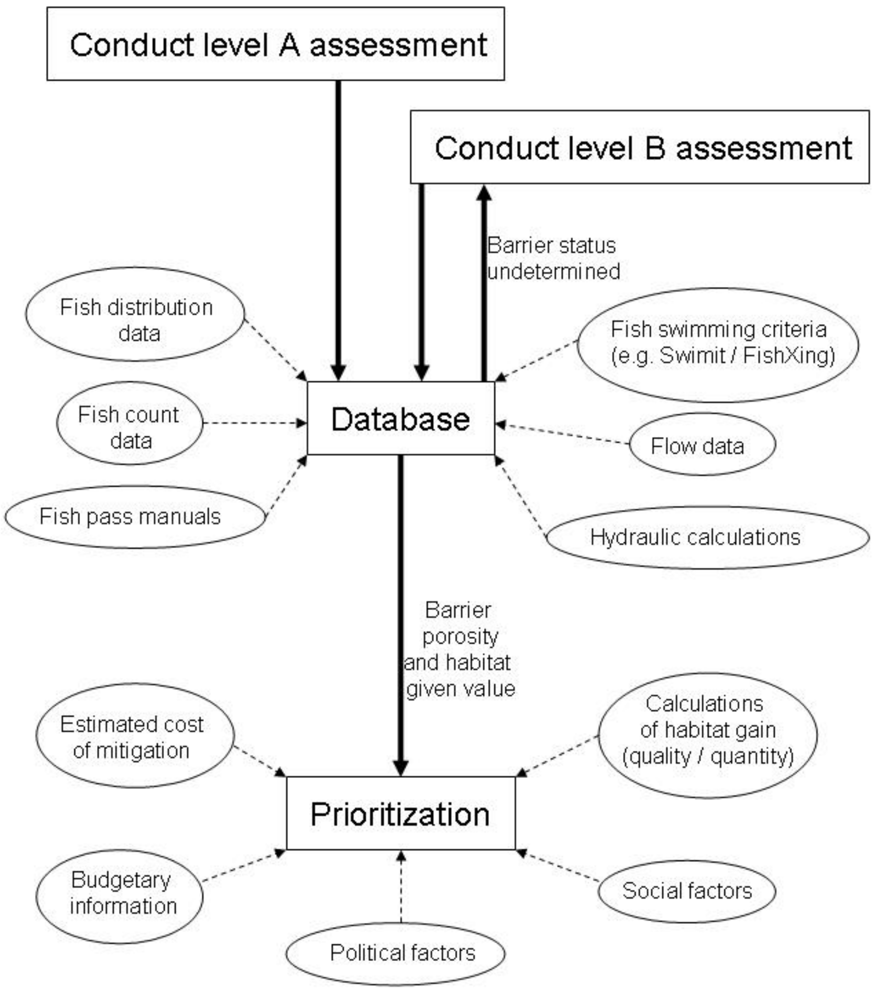

Figure 5. Process of information transfer (solid arrows) over three primary (boxes) stages of the recommended methodology from (1) assessments of barrier porosity (Level A and B); to (2) inventory (database) of barriers; to (3) prioritization. Relevant external databases and references (ovals) provide additional information (dashed arrows) to enhance quality of information at each successive stage.

A cohesive strategy for barrier assessment must be developed at the outset by the co-ordinating agency in collaboration with associated stakeholders to meet strategic objectives. This may relate to specific target species or to regions and may be dependent on scarcity of existing information on the fish migration barrier network. GIS based tools can be used to identify and prioritize appropriate areas for surveys as described by Nislow and Mendez (2007) (see review). It is envisaged that a phased approach will be adopted in which prioritization is based on a regional context in order to most efficiently meet obligations defined by the WFD. Likewise, the development of the methodology should be considered from a long-term perspective and, thus, it is recommended that the proposed techniques should be refined during a process of incremental improvement.

9.1. Fish barrier porosity assessments

A full (extended) reference guidance manual to migration barrier field assessment (appendix 1); reduced guidance manual to be used in the field (appendix 2); and field assessment forms (appendix 3), have been developed and are presented as part of this report. It is envisaged that the survey team use the reduced field guidance manual and assessment forms during surveys in the field, but will be familiar with and have access to the full reference manual for additional information on fish passage criteria and types of barrier.

All field assessment procedures must follow the most stringent Health and Safety guidelines and policies as defined by the participating agencies and after appropriate risk assessments have been conducted. Considerations of safety must always override data collection protocols as suggested in this report.

The holistic barrier assessment protocol outlined by the WDFW (Fig. 1) is an appropriate template for a methodology for the British Isles. It is recommended that the assessment team comprise of a minimum of two individuals trained in standard topographic surveying techniques. Before a survey is initiated it is important that the assessment team has been appropriately trained in the assessment technique and health and safety procedures as defined by the surveying agency. A general "rule-of-thumb" is that surveys should be conducted under conditions that approximate to base-flow (i.e. 50% exceedance flow), as the structure may be inaccessible or obscured from view (e.g. due to turbidity) during periods of spate or flood. However, for certain types of structure (e.g. culverts) it is necessary to conduct the survey during periods of low or high flows as it is under these conditions that the structure may become impassable. In cases where the team must enter the water, there are also obvious health and safety implications associated with flows and a full risk assessment must be conducted and mitigation procedures followed.

9.1.1. Level A assessment:

Assessments of barriers to fish migration are biased towards guidelines for culverts and the upstream movement of North American species of salmonids (e.g., Clarkin *et al.*, 2003; Coffman, 2005; Taylor and Love, 2003). The Coffman (2005) methodology is exceptional in that it considers multiple species by generalizing fish passage efficiency based on three species guilds defined primarily by the mode of swimming employed. The methodology may, therefore, be most applicable to the British Isles in which multiple species must be considered. For culverts, Coffman (2005) developed three models which follow the same format with only the threshold values at each level varying depending on the species guild the model is designed for. This methodology is also relatively simple to use in the field. More research is required to improve on fish passage criteria for several non-salmonid species, and to validate the fish passage efficiencies for these species in the field.

During Level A surveys, the assessment team will follow the standard protocol developed by the WDFW (Fig. 1). The Level A assessment comprises of two sections: (a) site description, physical characteristics, and basic water velocity measurements; and (b) subjective assessment of barrier porosity for target species / life-stages or species guilds. On locating a barrier, an assessment form (appendix 3) is completed, with reference to the reduced field guidance manual (appendix 2). The assessment form is designed to be user friendly based primarily on a “check-box” system. The following information is recorded:

<u>(a) Site description, physical characteristics, and basic water velocity measurements:</u>

- Name of assessor;
- Date and time of assessment;
- Antecedent conditions (e.g., heavy rain, snow, drought);
- Description of current flow conditions (e.g. low, moderate, spate, flood);
- Location of barrier (GPS coordinates);
- Ownership – if known;
- Barrier type (e.g., type of dam, culvert, weir, natural barrier) ;
- Digital image identification (the assessment team will be required to take digital images of the structure, including from the upstream and downstream perspective; and in cases where the structure might create a hydraulic barrier, 10 sec digital film footage should be provided). A unique id should be Included in the image. A survey rod should also be incorporated into the photograph to give perspective.
- Field sketch and description of the barrier indicating dimensions and incorporating details such as direction of flow, position of the level and any landscape details that are not captured by the digital image.
- Channel width.
- Structure dimensions: including height, width, length, water depth and head difference, culvert diameter, and longitudinal profile of channel gradient (more details provided for specific structures in the field guidance manual appendix 1 and 2). This information is collected using standard survey techniques (rod and level).

- Transect of surface, substrate, and mid-column (measured at 60% depth) velocity measurements taken at appropriate points relative to structure. A unidirectional electromagnetic flow meter should be used.
- Presence or absence of a fish pass (in the case of culverts an assessment of whether the culvert has been modified e.g., placement of baffles within culvert barrel, or weir and pools at the outflow).
- Comment of apparent effectiveness of fish pass or culvert modification (e.g. is it currently blocked with debris or silt?).
- Estimate of percentage of river / stream flow passing through the fish pass.
- Comment on ease of conducting assessment.
- Comment on whether the barrier may potentially create a hydraulic impediment to fish movement and recommendation for a Level B assessment.

(b) Subjective assessment of barrier porosity:

Based on details of fish passage criteria for each target species / life-stages or species guilds and descriptions of structure type provided in the field guidance manual, the assessment team is expected to form a subjective opinion on whether the impediment presents a negligible, partial, or complete barrier to fish movement in both the upstream and downstream direction. The assessor will use the “check-box” system to record opinion. This subjective assessment of barrier porosity will form the basis of a scoring system which will be refined at the data input stage based on descriptive and quantitative information relating to physical characteristics of the barrier, and potentially further information collected during a Level B assessment. The score will ultimately be used during prioritization.

During the Level A assessment, a value of 0 represents a complete barrier to movement of the target species / life-stage or species guild, and 1.0 is allocated to barriers that are passable. Two intermediate scores are given to structures that are considered to be partial barriers based on subjective evaluation of impact on fish passage as being high or low. Definition of barrier porosity is provided in the field guidance manual as:

(i) Complete barrier (value = 0):

It is of the opinion of the assessor that the target species / life-stage, or species guild can not pass the barrier (e.g. unpassable falls with no fish pass present) or it is known that fish are unable to pass because the species distribution comes to an abrupt halt at that point.

(ii) Partial high impact barrier (value = 0.33).

It is the opinion of the assessor that the barrier represents a significant impediment to the target species / life-stage, or species guild, but some of the population (e.g. < one-third) will pass eventually; or the barrier is impassable for a significant proportion of the time (e.g. > two-thirds). Culverts represent good examples of partial barriers if they impede fish during periods of high or low flow events.

(iii) Partial low impact barrier (value = 0.67).

It is the opinion of the assessor that the barrier represents a significant impediment to the target species / life-stage, or species guild, but most of the population (e.g. > two-thirds) will pass eventually; or the barrier is impassable for a significant proportion of the time (e.g. < one-third). Culverts represent good examples of partial barriers if they impede fish during periods of high or low flow events.

(iv) Passable barrier (value 1.0)

It is the opinion of the assessor that the barrier does not represent a significant impediment to the target species / life-stage, or species guild, and the majority of the population should be able to pass during the majority of the period of migration (movement). This does not mean that the barrier poses no costs in terms of delay, e.g. increased energetics, or that all fish will be able to pass.

In the event that porosity is undetermined for specific target species, especially in cases where more information is required in relation to velocities at hydraulic barriers, a Level B assessment may be sanctioned at a later date.

9.1.2. Level B assessment:

Data collected during Level A surveys will be assessed by experienced personnel at the data input “inventory” stage. During this phase it may be possible to refine subjective assessments of barrier porosity based on the information provided and other available data (e.g. population distribution). High velocity flows that characterize many structural impediments may constitute hydraulic barriers because they exceed the swimming capabilities of the fish and limit their ability to pass. In some cases, it may be judged that fish passage efficiency at hydraulic barriers remains undetermined, and the barrier will be designated as U (unknown or undetermined) . If it is considered that the barrier, or series of barriers, represents a critical “bottleneck” from the perspective of the fish migration barrier network, a more detailed survey may be sanctioned in order to acquire finer resolution information. A Level B assessment will require experienced staff to design and conduct a more detailed survey of physical characteristics and collect more detailed hydraulic information (e.g. 3-dimensional velocity measurements or hydraulic modelling e.g. Computational Fluid Dynamics). A good example of an in depth hydraulic survey conducted to assess the fish passage efficiency of a series of weirs is described by Winter and Van Densen (2001).

9.1.3. Level C assessment:

For critical barriers that are identified as having potentially significant impacts on fish populations, or are located at key sites within the catchment from the perspective of accessibility to suitable habitat, high resolution information on fish passage efficiency is required. The removal of, or development of mitigation strategies for, large dams that impound water for hydropower or water supply is costly and will require consideration of both social and political factors. Any prioritization mechanism will need to adequately factor in these costs in additions to potential benefits. Due to the significance of these decisions, it is highly recommended that fine-resolution information on fish passage efficiency is first obtained by employing Level C assessments in which well designed telemetry studies are conducted by independent parties. A coarse resolution rapid assessment methodology, while useful at the catchment and wider scale, will not provide sufficient information on which important decisions regarding dam removal or mitigation should be based. Level C assessments will provide percentage fish passage efficiency values and information relating to temporal variability and length of delay and as such will improve on the simplistic scoring mechanism used under the coarse resolution rapid assessment tool.

9.2. Field trialling and validation

Field trialling and validation of barrier porosity assessment protocols is one of the principal determinants of the efficacy of the methodology adopted. The majority of methodologies that are currently employed to assess barrier porosity (Coffman, 2005 being a notable exception) were developed with inadequate trialling and validation and thus their efficacy must be questioned. It is strongly recommended that a robust programme of trialling and validation is employed to collect empirical data for fish passage efficiency (using mark-recapture and / or telemetry techniques) associated with multiple barrier types, and used to compare with results of the “coarse-resolution rapid-assessment” subjective methods. It is important that mechanisms are in place to feed back the results of validation to the iterative process of assessment development, thus enabling incremental improvement of the methodology.

Tests are also required to determine degree of variation associated with subjective assessment. Multiple personnel should conduct the assessments for defined barriers and the reasons for significant discrepancies in results investigated in order to refine the assessment criteria.

9.3. The National Fish Passage Barrier Network Inventory

The recommended protocol requires that, once completed, the Level A assessment forms are returned to a central national database (e.g. maintained by the EA in England and Wales, and SEPA in Scotland). The Level A assessment form should be scanned and stored as an image along with other image or film files in the central database to enable future interrogation. At this stage, expert personnel will assess the information provided and, where necessary, refer to additional databases and reference manuals to refine the data. For example, the ownership of the structure can be verified and map data can be used to assign stream order (a useful factor during prioritization). Useful supporting data, often available via internet sources, may include the following:

- River flow data for date and time of Level A assessment (e.g. National Flow Archive);
- Fish passage criteria based on swimming capabilities (e.g., FishXing and Swimit);
- Information on timing of fish migrations in order to predict most likely flows and fish passage efficiencies based on swimming capability data;
- Scientific literature for fish passage (e.g., based on fish swimming capabilities and behaviour);
- Engineering plans of the structure. This is especially important when the assessment is incomplete because important features were obscured from view at the time of the survey (e.g., tidal sluices etc.);
- Fish passage design criteria: the EA has developed one of the most detailed guidelines on criteria for multiple fish pass designs;

- Fish count data (e.g., from fish ladders at Hydropower dams);
- Fish population distribution data (e.g. as provided by the district salmon fisheries boards or EA surveys);
- Data relating to habitat assessments.

Ultimately, the expert personnel will use the additional information to verify or refine the barrier porosity score assigned by the assessment team. It would be prudent to regularly compare the final barrier scores given at the database stage with those assigned by the field assessment teams as a means to monitor improvement in the quality of data collection. Each barrier will be assigned a series of scores, one for each individual species / life-stage or species guild, based on the subjective assessment. A total aggregate score will also be calculated as the sum of all the species/ life-stage or species guild scores divided by the number of species/ guilds. Under some circumstance it may be decided that a more detailed Level B or C assessment is required to improve on the barrier porosity value assigned. The scoring system can be adapted to accommodate alternative objectives of restoration by weighting the values for species that have greater economic or conservation significance, and / or weighting values of barriers based on stream order.

It is important that the database software selected meets the standards required by the co-ordinating agency, and compliments computing platforms and other databases currently employed. Current GIS techniques provide a powerful tool to illustrate the geospatial data associated with a fish passage inventory (note that SEPA has started compiling fish passage barrier information in the form of a GIS model). GIS may be supported by a range of database types, from the simple (e.g. Microsoft Excel) to the more complex. The EA's NFPIPM was developed using an Access database. However, SEPA's GIS platforms are currently supported by Oracle database software and thus this may prove to be the most optimal selection. It is recommended that a web-based fish barrier inventory is developed so that all stakeholders can access information maintained by the co-ordinating agency and so the objectives of the methodology can be disseminated to the public.

9.4. Prioritization of barriers for removal or mitigation.

At the national scale, the project may be considered from a multiple stage perspective in which the co-ordinating agency and other stakeholders prioritize catchments for consideration based on meeting objectives set within the constraints of political and economic frameworks. For example, waters may be prioritized, from the perspective of WFD requirements, giving highest values to “natural waters”, followed by “heavily modified waters”, and then by “artificial water bodies”. Alternatively, selection of waters could be based on the known distribution of target species and by expert judgement (Kroes *et al.*, 2006). It is recommended that the project is first trialled based on data available for a pilot catchment for which a fish migration barrier network is relatively well defined and benefits may be easily measured against current status of information on fish stocks and habitat availability.

Once a fish migration barrier network has been defined (either partial or complete) and barrier porosity scores assigned to each structure, a mechanism is required that can prioritize barriers for repair, removal, or mitigation taking into consideration the costs and benefits of doing so within the constraints of a limited budget. To do this, information is required for the cost of mitigation or removal (e.g., engineering and constructions costs), and potentially economic evaluations associated with lost power or water supply and associated social, political, and administrative impacts. Considering the requirements of the WFD, benefits relate to an increase in Ecological Status or Potential when viewed from the perspectives of catchment, regional, or national scales. This may be more easily defined as length, area, or some other measure of quantity of riverine habitat that will become accessible as a result of actions taken. It is feasible that during prioritization, barriers located on higher ordered stream may be given a greater weighting with respect to their removal or mitigation due to the disproportionately larger area that might be made available as a result of restoration. Although many prioritization mechanisms consider benefits in terms of habitat quantity, there is a need to incorporate habitat quality into the prioritization process. It is not efficient to consider habitat quantity alone, as increasing accessibility to large areas of poor quality habitat may have lower overall benefit relative to smaller areas of optimal habitat. However, the cost of restoring suboptimal habitat could potentially also be factored into the decision making process.

Alternatives to measures of habitat quantity and quality include predictions of increased fish (or indeed some other taxa) productivity or population viability. Ultimately, the most sophisticated models might make these judgments based on additional information on population dynamics (e.g., Letcher *et al.*, 2007) and identification of "population bottlenecks" that limit productivity and population growth (see Armstrong *et al.*, 2003). Indeed, it may be argued that it is important to set objectives that are quantified, e.g. by defining the abundance of species in a river system that is necessary to maintain a sustainable population (Kroes *et al.*, 2006). Unfortunately, understanding of population dynamics for multiple species over a range of catchments / regions is currently not at a stage that will facilitate the realization of such aspirations over the short term.

The most simplistic prioritization methodology may be based purely on considerations of habitat accessibility and assumptions that all habitats are equal and financial considerations are non existent. O'Hanley and Tomberline (2005) define "accessibility" as the ability to access habitat upstream of a single, or multiple, barriers. Accessibility is calculated as the product of all downstream barrier passability values. For Level A and B assessments, the value are represented as either 1 (no barrier), 0.67 (low impact partial barrier), 0.33 (high impact partial barrier), or 0 (complete barrier). However, in cases where Level C assessments are conducted in which percentage values of porosity are attained, fine-resolution estimates of accessibility will be possible in which the percentage of the population that reaches the defined habitat may be estimated. This definition of accessibility, however, assumes that barrier porosity values are independent of each other and that a fish that is able to negotiate one barrier is neither more nor less likely to pass successive barriers (O'Hanley and Tomberlin, 2005). In reality, this is an oversimplification because fatigue is likely to play a role as fish negotiate multiple barriers. As suggested by Haro *et al.* (2004), the rate and distance of successive attempts to pass velocity barriers may be influenced by the extent to which glycogen stores or other metabolic resources are exhausted. However, it may also be possible the migratory efficiency of an individual will increase with time as a result of increased experience or some "training effect". Alternatively, in the event that fatigue does not occur, it is theoretically possible that if two successive barriers are "identical" and thus are assigned the same score, the proportion of the fish that pass the second barriers will be 100% as they were selected from the larger population at the first barrier. It is, however, clear that a more robust cost: benefit analysis is needed in which the quantity (area or river length), and quality of habitat that will become accessible if a series of barriers are removed or mitigated for is assessed in conjunction with analysis of the costs of repair.

As discussed in the review section, Scoring and Ranking systems are the most common method used to prioritize barriers for mitigation or removal. This methodology depends on a cost: benefit ratio calculated by considering the scores assigned to each barrier and costs of mitigation relative to measures of improvement of habitat connectivity. Barriers are then assigned a rank based on the cost: benefit ratio. O'Hanley and Tomberlin (2005) highlighted the problems of using this technique in terms of considering barriers as independent entities and used a real life data-set to illustrate how low level of efficiencies may be obtained. For the reasons previously discussed, we do not recommend that a Scoring and Ranking system is employed as a prioritization tool in the context of the British Isles.

Current methods for prioritizing fish passage barrier removal and repair decisions, which range from simple scoring-and-ranking type procedures (Pess et al. 1998, WDFW 2000, Taylor 2003) to much more sophisticated optimization based methods (Paulsen and Wernstedt 1995, Kuby et al. 2005, O'Hanley and Tomberlin 2005), all presume perfect certainty and full availability of data concerning the number, location, current passability level, and repair cost of barriers. In many real-world planning situations, such as in the UK, however, much of the information may be uncertain or incomplete either for specific sets of data or within particular planning areas. Such information gaps present a challenging problem from an operational planning perspective, as current methods fail to adequately incorporate the key uncertainties involved in the decision making process.

A case in point is the often incomplete inventory of existing passage barriers across a planning region. In the absence of full scale surveys, the resulting mapped network of passage barriers may only be partially complete for one or more of the component catchments. Consequently, because the full number and location of barriers may be unknown before initiating a program of barrier removal and repair, determining the potential impact of repairing a given barrier and, likewise, the construction of an efficient removal strategy becomes an exceedingly difficult task due to the presence of unknown or “hidden” barriers between any given pair of known, adjacent barriers.

As a crucial step in devising more robust decision making methods for passage barrier removal and repair, functional and realistic probability models must first be developed to characterize each of the key uncertainties involved. With regard to potentially incomplete data on the number and location of passage barriers (i.e., the configuration of the barrier network), an intuitive and rather fitting way of describing this type of uncertainty is with a Poisson process. A Poisson process is a very well-known stochastic process for modelling independent random “events” over time or space. Common examples include the number of calls received by a switchboard or the number of customer arrivals into a simple queuing system per unit time. By letting an event correspond to a barrier, a Poisson process can be extended in a natural way to model both the number and spatial position of any potentially intervening *hidden* barriers between known, adjacent barriers. As a Poisson process is characterized by only a single parameter representing the mean number of barriers per unit length of stream, which can be easily estimated from a dataset containing a more or less complete inventory of barriers from one or more well surveyed stream basins, the information requirements imposed by it are minimal.

Uncertainty regarding both barrier passability and repair cost can also be handled in a fairly straightforward manner using relatively simple univariate parametric probability distributions. Since barrier passability, which expresses the proportion of fish that can pass a particular barrier, must necessary lie within the continuous range 0 (for a completely impassable barrier) to 1 (for completely passable instream structure), a natural choice is to use a beta distribution. A notable feature of the beta distribution is its high flexibility. Because it can take on a wide range of shapes, it can be easily adjusted to describe either observed or assumed distributions for barrier passability within a particular planning area.

For modelling repair cost, a rough but effective approach, particularly if data is limited, is to use either a uniform or triangular distribution. A uniform distribution is useful when a minimum and maximum value for repair cost is known and cost is equally likely to take on any value within this range. If in addition to having minimum and maximum values, a most likely value for cost can be provided, then, a triangular distribution might be suitable. Certainly, if more data is available, almost any theoretical statistical distribution can be quickly and easily fitted via maximum likelihood estimation methods to describe potential barrier repair costs.

With formal probabilistic models in place for modelling each of the main uncertainties, exact and heuristic solution methods can subsequently be developed to find optimal or near optimal solutions to the problem of passage barrier removal and repair. Previous work by O’Hanley and Tomberlin (2005) has shown how dynamic programming techniques can be applied to optimally solve, both quickly and easily, a deterministic version of the problem in which all information is assumed to be complete and certain. In a fairly straightforward manner, the same basic approach can be extended to handle the three key types of uncertainty discussed above – barrier network configuration, passability, and repair cost – by applying *stochastic* dynamic programming (SDP) techniques. More specifically, SDP can, subject to a chance type constraint on total cost, be used to maximize the expected net gain in accessible upstream habitat given uncertainty regarding the network configuration, passability and repair cost of fish passage barriers. A chance constraint on total barrier repair cost ensures that the probability of exceeding the available budget is never allowed to exceed some user-specified threshold (e.g., there should be at most a 5% chance that the total cost will exceed the given budget). Additionally, simpler heuristic based approaches can also be developed for the stochastic version of barrier removal and repair, which normally have the advantage of being much faster to run and can in some cases prove easier to implement from an operational standpoint.

The optimization and heuristic modelling approaches described by O'Hanley and Tomberlin (2005) to solve the Fish Passage Barrier Removal Problem provide a starting point from which to efficiently prioritize barriers removal or mitigation to maximize net habitat gain within the constraints of a limited budget. However, these modelling techniques rely on oversimplifications of the barrier negotiation problem (for example they do not allow for fish who encounter an impassable barrier to backtrack and try an alternative stream). While the optimization approach of O'Hanley and Tomberlin (2005) is valid, what is necessary to achieve the full potential of the approach is a modeling methodology capable of accurately representing the passage of fish within the river network (including for example the fatigue, backtracking, non-independent barrier porosities and sub-optimal habitat acceptance problems described above) and enabling the greatest levels of flexibility for decision makers to consider varying management options. Although the development of these methodologies require expertise in the modelling protocols described, they represent a useful tool for prioritization of barrier mitigation or removal when inventories of fish passage barrier networks become increasingly complete and should be strongly considered as a potential option for this project

It may be suggested that the development of "state-of-the-art" simulation models, while capable of producing near optimal solutions to problems of prioritization, will prove too costly in terms of development, time, and requirements for specialist expertise, and hence should be sacrificed in favour of more simplistic techniques to meet short term targets (despite the fact that simplistic models may be significantly less effective). However simulation methodologies would not have to be developed from scratch as similar approaches have already been developed and are currently widely employed by other sectors (e.g. transport system planning and pedestrian flow modelling). Using these models as a basis of a prioritization tool would significantly reduce development cost.

Generic tools for allocation and pathfinding operations within networks are available within GIS systems for both vector and raster data. The more familiar operations performed on dendritic systems such as river networks concern flow, e.g. in studies of drainage or stream ordering. However, the methods developed for rectilinear networks (e.g. roads) are probably of more interest for understanding how barriers to fish movement affect the ecological status of rivers. While the more specialist tools for modeling road networks are mentioned below, generic GIS packages are capable of building moderately sophisticated models which might at least serve to develop initial ideas. For example, the "value" of any point on a river system might be expressed in terms of the costs of arriving there, incorporating distance (as a proxy for energy expenditure) or some measure of impedance determined by the river's characteristics (a friction surface), and barriers with various levels of permeability. These "costs" may be balanced against the "gains" of successfully negotiating the journey in terms of breeding habitat quality. This approach (often termed least-cost path analysis) has previously been used in studies of wildlife movement corridors and for assessing the impacts of habitat fragmentation on species (e.g., Walker and Craighead, 1997; Davidson, 2004; Drielsma *et al.*, 2007). The advantage of GIS systems for such calculations is their inherent ability to handle mapped data which might greatly assist analysis over large geographic areas. Their disadvantage is a lack of specialist modelling tools for rectilinear networks but these are available from the transport modeling community.

The closest parallels within transportation modelling are the concepts of 'Accessibility' and 'Severance'. Accessibility Planning (Department for Transport,

2005) has been a requirement for Local Authorities in England since 2005 (as part of their Local Transport Plan submissions) and relates to measuring the proportion of the population within (for example) a five minute walk to the nearest doctor. Severance (Department for Transport, 2003) examines more specifically the difficulties created by hazardous situations (for example pedestrians needing to cross a busy junction) and the potential accessibility benefits that ensue from mitigating such barriers. Transport modelling software packages are available which are specifically designed to assess either accessibility (‘Accession’ – Citilabs, 2008) or more directly with the movement of objects through connected networks. These models (for example Aimsun – Transport Simulation Systems, 2008) are used to simulate the decisions being made of travellers in a road network and while clearly the behaviour of road users is different to that of fish, there are parallels which can be drawn.

- The ‘Intervening Opportunities Model’ is used to represent travellers searching for an appropriate destination and could be customised to represent a decision to either spawn at the current (possibly sub-optimal) location or continue upstream.
- ‘Way-Finding’ models are used to represent travellers who are unfamiliar with the road network and could be customised to represent the choice of direction for fish as they travel through the stream network.
- ‘Generalised Cost’ is used to provide an overall measure of time and distance for a journey and this could be customised to represent (for example) total required effort to reach a spawning location.
- ‘Restricted Access’ is used to represent areas of the network where only certain types of object are allowed (e.g. pedestrian areas or bus lanes). Combined with ‘Incidents’ (which represent problems in the network where progress is restricted or at worst prevented) form clear parallels with barriers to movement in the stream network and the models could, therefore, be used both to represent behavioural responses such as fish

returning downstream to try alternative locations and allow the progress and behaviour of fish to vary by species.

9.5. River classification scheme

To help the British Isles meet the obligations set under the WFD, a key objective of this project is to provide recommendations for a river classification scheme that illustrates the impacts of barriers on fish migration. SEPA require a GIS based map to illustrate and quantify the proportion of Scottish rivers that fall within the categories defined as "high", "good", "moderate", "poor" and "bad" ecological status based on the impact of barriers to fish migration. This can be achieved in two phases.

First, the barrier porosity assessment scoring system may be used to calculate cumulative accessibility values for river habitat upstream (or downstream) of individual barriers. For any target species, river length and accessibility values can be calculated to describe the cumulative impact of barriers present. To illustrate this, a simplistic river migration barrier network (Fig. 6) can be considered, in which five barriers (a-e) have been assigned subjective barrier porosity scores. In this scenario, the value of 0 (impassable) is altered to 0.01 to accommodate limits in confidence associated with the subjective technique, and to allow multiplication of zero scores. This is based on the premise that a series of impassable barriers should be given a lower score than any single impassable barrier because the impact on accessibility and cost of mitigation will be greater. When considering upstream migration, the score for the length of riverine habitat upstream from point e to the next barrier, or the end of the river system (i.e. source of the headwater tributary), is the product of all five downstream barrier scores. Using GIS techniques, a map can be constructed to quantitatively illustrate the positive relationship between accessibility and stream order, or the negative relationship between accessibility and number of barriers present. This approach may be adapted to consider sections of river independently of each other, using a weighting for stream order calculated using the Shreve methodology to account for disproportionate catchment areas impacted. The most downstream reach of the example system (Fig. 6) is most heavily impacted by barriers because it has the highest number of structures, but is also situated on a high stream order section and impacts will

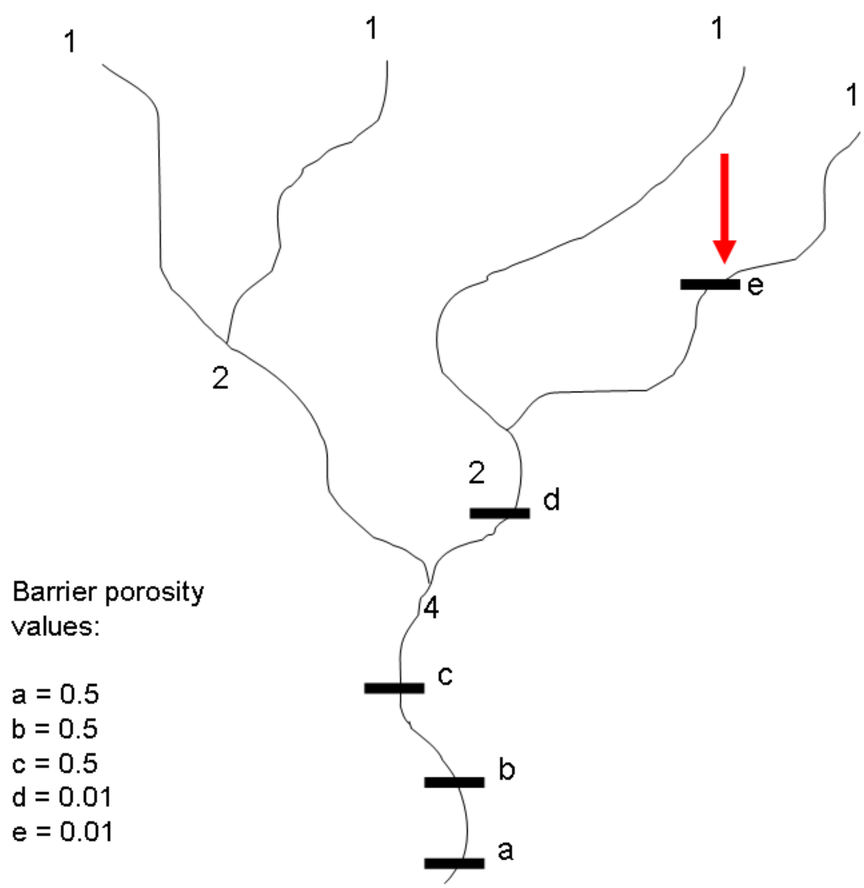

Figure 6. A simplistic example of a hypothetical fish migration barrier network where obstacles are illustrated as solid bars. Each impediment has been given a subjective porosity score, and the rivers assigned a value for order based on the Shreve methodology.

be disproportionately greater. Also, dependent on project objectives, different target species may be assigned alternative weighted values, e.g., so that the impact on salmonids may be given higher credence than that for non-salmonid species (or vice versa).

The second phase requires that the model be calibrated for each catchment. Threshold values for the classification of "high", "good", "moderate", "poor" or "bad" must be set. As these threshold values will to some extent be arbitrary and influenced by political frameworks, it may be argued that their definition must be the responsibility of the policy makers. If the definitions of classification threshold values are based purely on ecological grounds, decision makers must be provided with information based on understanding of the relationship between values of cumulative barrier porosity and ecological status, most feasibly by using fish population response as an indicator. This is currently not possible for many systems and species and more research on population dynamics and the impact of barriers relative to a multitude of other influential factors is required to provide the information necessary to form policy.

Species specific objectives may be used to define threshold classification values. For example, UK Eel Management Plans aim to achieve 40% escapement of adult eel biomass. This value may be used to assign a threshold for this species, e.g., any river for which this is not realized may be classified as "poor" (although the same river may achieve a higher classification when other species or the aggregate score are considered). Some critical value of return rates may be used when considering anadromous salmonids. For example, 5% "smolt-to-adult return" (SAR) ratio, or the minimum number of adult spawners required to maintain population sustainability (if known).

Subjective methods may be used to set classification boundaries, albeit with lower levels of confidence, in which arbitrary designations are based on population status (which may be used to calibrate a model of cumulative habitat accessibility scores). For example, when considering anadromous species, a river may be classified as having a "high", "moderate", and "poor" accessibility status if 100%, 50%, or 0% of target species maintain sustainable populations upstream of anthropogenic barrier for a specified period of time. Unfortunately, there are multitudes of other factors that influence populations, and the potential to assess the relative impact of barriers to fish migration is a difficult task, requiring information on population status and recruitment / escapement in conjunction with assessments of barrier permeability. It is recommended that in the first instance, a coarse resolution approach is adopted in which values of cumulative accessibility and barrier density (number of barriers per km) are used in conjunction with available population data to define river classification thresholds. As little is known about the population status of some of the target species (e.g. river lamprey), it is recommended that efforts are initially focused on salmonids, or other "umbrella" species, for which there exists a higher degree of confidence in population status data. It is strongly recommended that a proportion of future resources available are committed to developing an incremental programme to iteratively improve population status and distribution data for the selected target species.

9.6. Time-table for implementation

The time-table for implementation as proposed by SEPA (Table 13) requires that a methodology for assessing the impact of barriers to fish migration is fully implemented over four phases by December 2011.

It is recommended that field trialling and validation components include a robust empirical assessment of barrier porosity utilizing appropriate techniques (e.g., mark recapture / telemetry), and that the results be used to iteratively improve the protocol. It is strongly recommended that, as part of this project, the time-table be developed to accommodate the integrated development of the database inventory, GIS map, and a prioritization methodology. Independent development of the three principal components of the methodology: barrier assessment, database construction, and development of the prioritization tool, must be avoided.

Table 13. Time-table for implementation of fish migration barrier assessment project.

Date	Objective
End March 2008	Present an interim report on methodologies and initial recommendations to the steering group.
End April / May 2008	Present a complete assessment report on methodologies to the steering group. Convene workshop to present results and recommendations (End of Phase 1).
April 2008	(Start of Phase 2). Begin preparations for field data collection for trialling and validation of selected methodology.
End May 2008	Begin field data collection for trialling and validation of methodology.
October 2008	(Start of Phase 3). Begin reparations for the roll out of methodology for assessing the porosity of obstacles to fish passage.
End December 2008	Present completed report detailing trialling and validation results for the selected methodology (End of Phase 2).
January 2009 – December 2011	Roll out of methodology for assessing the porosity of obstacles to fish passage.

10. CONCLUSIONS

Riverine habitat fragmentation is a major impediment to the British Isles and other European Member States meeting obligations set under the WFD to achieve Good Ecological Status or Good Ecological Potential (in the case of heavily modified water bodies) by 2015. Habitat fragmentation primarily results from river development in which anthropogenic structures create barriers that interrupt ecological processes, described by the River Continuum (Vannote *et al.*, 1980) or Flood Pulse (Junk *et al.*, 1989) concepts. Structural barriers can partially or fully block the movement of fish between essential habitats and consequently negatively impact population status (Lucas & Baras, 2001), providing one of the clearest measures of a loss of ecological status. There is a need to quantify and spatially illustrate the magnitude of impacts to determine and then classify the status of rivers within the British Isles as defined under the WFD as “high”, “good”, “moderate”, “poor”, and “bad”.

The high abundance of artificial barriers that impede fish movement is an artifact of a long historic legacy of river development throughout Western Europe. For example, in England and Wales, it is estimated that 2,500 obstructions, the majority of them small in scale, prevent or reduce fish migrations (DEFRA, 2006). The effective identification and removal of, or mitigation for, barriers to fish migration is one of the most efficient means of restoring habitat connectivity and consequently fish populations (Roni *et al.*, 2002), and thus also ecological status. This requires identification of the fish migration barrier network within the catchment; assessment of barrier porosity; construction of an inventory of impediments; and development of mechanisms that enable prioritization of barriers for mitigation or removal. The need to adopt a catchment-scale approach as part of a holistic management plan to solve the problem of habitat fragmentation when developing a national strategy is well recognized under the WFD (Kroes *et al.*, 2006). This report critically reviews methodologies currently being employed to assess the porosity of barriers to fish migration; the use of databases to store and maintain pertinent data related to barriers; and the mechanisms used to prioritize barriers for removal or repair. The report provides recommendations for how currently available methodologies may be adopted and adapted to facilitate the development of a tool appropriate for implementation within the British Isles. A field guidance manual (appendix 2) and field barrier porosity assessment form (appendix 3) have been developed. The construction of a national map illustrating rivers and associated accessibility of habitat determined by cumulative barrier porosity based on subjective assessment is considered, and how appropriate thresholds can be defined in the context of WFD classification of rivers or catchments, discussed. Caveats to the methodologies are provided, gaps in current understanding identified, and recommendations for future actions detailed. Ultimately, an opportunity exists to develop a “state-of-the-art” national methodology that will assess and record the impacts of catchment-scale fish migration barrier networks and provide a tool to efficiently prioritize barriers for removal or repair based on benefit: cost analysis.

This report critically reviews a wide range of methodologies employed in the United States and Europe to assess barrier porosity to fish movement. The use of telemetry techniques (e.g. Passive Integrated Transponder or radio) provide the most effective means of defining fish passage efficiency at barriers. However, these techniques do not provide a practical solution for the development of a "coarse-resolution rapid-assessment" methodology to provide a national-scale assessment of structural barriers. The most advanced methodologies currently available to assess and record barriers to fish migration at a regional / national level have been developed in the United States, primarily along the western seaboard, driven by the requirement to restore populations of Pacific salmon. As a result, the methodologies are somewhat biased towards considerations of species of salmonid, and usually in relation to the upstream migration of adults. The requirements for a methodology to be employed within the British Isles must take into consideration the impact of barriers on multiple species in both the upstream and downstream direction. Therefore, current methodologies must be adapted to accommodate this, and as a result, fish passage criteria must be developed for all defined target species. As a result of decisions made by the project steering committee, this report considers the requirements of Atlantic salmon, brown trout, grayling, eel, river and sea lamprey, barbel, and chub.

This report does not provide guidelines for the design of in-river structures or fish passes as considerable information relating to design criteria already exist. It is also recognized that the impact of inadequately screened abstraction points has the potential to significantly impact fish populations. The identification and development of an inventory of abstraction points can prove particularly challenging as they may not be highlighted on maps or easy to see, even when conducting a river survey on foot. Abstraction points are particularly problematic for downstream migrating species and life-stages (e.g., eels, smolts, and kelts), and the provision of suitable screening structures can be expensive.

The proposed barrier assessment protocol consists of up to five phases. The first requires strategic evaluation and identification of survey areas based on paucity of data, conservation objectives, and socio-political factors. It is essential that all appropriate risk assessment procedures are conducted in line with the health and safety policy of the surveying agency before any field assessments are conducted.

Second, a Level A assessment of the barriers encountered during the survey will record location, ownership (if possible), and physical topographic features and water velocities associated with the structure. The identification of complete barriers to fish migration can be relatively straight-forward based on physical and velocity measurements. Partial barriers may not physically obstruct fish movement, but can create an impediment under specific flow conditions when depths are insufficient or velocities exceed swimming capabilities of the target species. Survey personnel will take digital images of the structure, record velocities at key locations, measure structure dimensions, and make subjective assessments of porosity for the target species based on the guidelines provided. The guidelines were developed after reviewing literature on fish passage criteria that are primarily based on knowledge of swimming performance. Unfortunately, current understanding of fish swimming capabilities is biased towards salmonids, and to a lesser extent some other North American species. Nevertheless, sufficient information (e.g. EA’s Swimit model) is available to develop basic fish passage criteria for some, but not all, target species and life-stages. However, concerns persist in relation to the quality of swimming performance data collected under highly artificial conditions (e.g., Haro *et al.*, 2004), and the lack of consideration of fish behaviour when defining fish passage criteria (Kemp *et al.*, 2005a,b, and 2006). Incremental improvement of the barrier porosity assessment protocol is dependent on enhanced resolution of data relating to fish passage criteria based on realistic measures of swimming performance for all migratory life-stages of the target species, and greater understanding of the significance of behaviour.

During the third stage of barrier porosity assessment, the Level A data is reviewed and refined prior to entry into the database. Additional information, e.g., in relation to fish passage design criteria or known population distribution for the target species, can be accessed at that point, and used to refine porosity scores. Based on the results of the Level A subjective assessment conducted for each individual species / life-stage, the barrier may be defined as passable (value = 1); low impact partial barrier (0.67); high impact partial barrier (0.33); not passable (value = 0); or undetermined (U).

In cases where the porosity can not be determined or where finer resolution information is deemed necessary, the fourth stage may result in the recommendation of a Level B assessment during which more detailed information, e.g., obtained by hydraulic modelling, is collected to enable a more robust porosity value to be defined. In this case, a fifth stage requires the results of the Level B assessment to be entered into the database.

Where the impact of specific barriers, or series of barriers, are considered significant, or where the removal or mitigation of the barriers have considerable social and economic implications (e.g., hydropower facilities), a Level C assessment should be considered. Level C assessments provide high resolution information, e.g. by employing radio-telemetry techniques. They should be conducted by appropriately experienced independent organizations in consultation with both the operators and regulators. Level C assessments may eventually become a component of the CAR licencing process in some cases. Nevertheless, in the absence of a Level C assessment, some measure of porosity must be determined and should be based on all available information (e.g. fish counter data and population distribution).

An essential requirement for the iterative development of the assessment methodology is to conduct robust programmes of field validation during which appropriate techniques, such as radio-telemetry, are employed. The results of field validation must be used to provide feed-back to facilitate the development process.

Both the EA and SEPA have initiated the development of databases to maintain information on structural barriers in England and Wales, and Scotland, respectively. SEPA's intention is to create an Oracle database to maintain the information supported by GIS which would allow open access to the data via the web. The EA database is based on Microsoft Access. They are not currently compatible. It is important that a common cohesive strategy is developed on which either a database for the entire British Isles is constructed, or each nation builds its own. The latter option will duplicate effort and may not prove to be an efficient use of limited resources. However, for pragmatic reasons, several national databases may prove necessary to accommodate differing regional policy objectives (e.g., consideration of cyprinids is of limited significance in upland Scottish rivers). There is a need for all parties to discuss individual requirements, and to decide whether a single database is appropriate, at the outset. System requirements must be stipulated. If a single database is to be developed, it is essential that the format for data collection be nationally consistent. It is also important to ascertain whether, and which, single or multiple agencies should take responsibility for database construction and maintenance (e.g., SEPA, EA, Scottish Natural Heritage, Fisheries Research Service etc.). It is strongly recommended that integrated development of assessment protocols, the database, and prioritization tools occur, in parallel. It may be necessary to build a consortium of agencies, academic institutions, and consultancies to achieve this objective in the most cost effective manner possible. Thus, there will likely be a requirement for agreement in relation to the ownership of intellectual property rights.

SEPA require that the database be supported by GIS to develop a national map of the fish migration barrier network. The map (to be developed over a four year programme) is intended to represent a valuable resource for regulators who are responsible for ensuring that actions are focused on the most effective measures to improve fish migration; operators, to provide a transparent and objective means of defining where mitigation measures are required avoiding protracted disputes with regulators; fishery boards and trusts for the purpose of prioritizing initiatives to improve fish migration; and the scientific community, to facilitate the study of fish population dynamics and provides opportunities to progressively improve the effectiveness of the criteria used to assess barriers. The map will also be used to illustrate the river classification scheme based on habitat fragmentation, defined as “high”, “good”, “moderate”, “poor”, or “bad”. To do this, there is a need to understand the significance of cumulative habitat accessibility scores that are calculated based on subjective assessments of barrier porosity in terms of fish population response, i.e. how inaccessible must habitat become before fish population exhibit a significant response. This will facilitate calibration of accessibility relative to ecological status or potential on which classification boundary thresholds values can be set. Ultimately, it is recommended that efforts be made to collect necessary information to determine population status for the priority catchments, and that this must be used in conjunction with measures of cumulative barrier porosity. Further research is also required to understand how population dynamics for a range of target species are influenced by habitat fragmentation (e.g., Letcher *et al.*, 2007). In the interim, definitions of threshold values may be based on the percentage of the catchment that is inaccessible to fish during a specified proportion of their migratory period as proposed under the UKTAG scheme.

While maps that depict the current status of fish migration barrier networks are a useful aid to policy makers, they do not provide a mechanism for the prioritization of restoration actions. At a national level, there is a need to prioritize catchments for restoration. For policy makers, these decisions may be based on a multitude of complex factors in which considerations of habitat fragmentation are placed in the context of other problems, e.g. water quality, water safety management, recreation, fisheries and biodiversity (Kroes *et al.*, 2006). The solution often needs to address a range of problems of which fish migration may be just one. Therefore, it is essential first to set clearly defined objectives at the outset after considering all demands. It is then important to identify the resources required to deliver the objectives, and to assess the feasibility of doing so within budgetary constraints. When considering only barriers to fish migration, it may be decided that those catchments for which sufficient resolution of data exists to define the barrier network should be considered a priority, as well informed decisions can be made relatively quickly (with the help of appropriate decision support tools). Consideration of those catchments that suffer from a paucity of information may be postponed until the resolution of data has been improved. However, this approach is not driven by the need to maximize the restoration of ecological status or potential. Indeed, the ranking and prioritization of catchments for actions becomes increasingly difficult when social and political constraints are also considered. For example, in California there is currently much debate as to whether limited funds should be directed at catchments where fish populations are the most critically threatened, or to concentrate on areas where populations are more robust and likely to result in a higher return rate when considering increases in productivity (CSCC, 2004). This scenario is true also within the context of the British Isles. For example, in Scotland, there may be a similar debate as to whether efforts should be directed at east coast rivers, where relatively stable and substantive populations of Atlantic salmon persist, or whether west coast rivers that maintain smaller, and possibly more threatened populations, should take priority. Kroes *et al.* (2006) suggest that priority waters might include those that are part of national or regional policy or agreed actions plans, or where stocks of anadromous and catadromous fish exist, or where there is potential to restore them. Ultimately, this decision must be taken having considered the opinions of all stakeholders and based on the objectives set in order to meet the requirements of the WFD. A multi-objective approach may be adopted in which other economic or management issues are considered in addition to the net gains in habitat or fish production (O'Hanley and Tomberlin, 2005).

Once priority catchments have been identified, it will prove impossible to fully restore all migration routes immediately. Instead, a phased approach, both from a temporal and spatial perspective, is required. Prioritization for action should be formed based on agreed objectives defined at the outset of the programme and within time-scales required to meet targets imposed under the

WFD (Kroes *et al.*, 2006). It is likely that several solutions might be identified that appear to enhance habitat connectivity. However, there is a need to decide on the most efficient solution that will maximize benefits and minimize costs. Thus, effective prioritization tools are required to support decision makers.

At the catchment-scale, once an inventory of barriers has been developed, a mechanism is required to prioritize those that could be removed, or mitigated for (e.g., provision of a fish pass), based on the magnitude of negative impact relative to positive gains attained. Benefits are commonly quantified as the net increase in accessible habitat, defined as quality-weighted area or length, or potential increase in fish productivity. In the context of the British Isles, the principle benefit of developing a similar prioritization tool is to enhance ecological status or potential as required under the WFD by re-establishing habitat connectivity. The restoration of populations of fish negatively impacted by habitat fragmentation can be considered an indicator for achieving this aim. Costs are often considered in financial terms, e.g. in relation to the removal or the structure; the provision of a fish pass; or lost hydropower or water storage capacity. However, other socio-political or administrative costs may be considered. Data quantifying costs and benefits are thus a necessary prerequisite for prioritization analysis.

The majority of methods reviewed on which barrier mitigation or removal decisions are based depend on simplistic scoring and ranking techniques (e.g. Pess *et al.*, 1998). Individual barriers are scored, based on a value of porosity, and then ranked in relation to the benefits (e.g. area of accessible habitat as a result of removal or repair) versus costs of mitigation. This methodology is relatively simple to apply, but is limited in that each structure is considered as an independent entity. As a result, scoring and ranking systems tend to be considerably less efficient than optimization models due to the lack of consideration of spatial dependencies among barriers, and an inability to readjust rankings during the process (O'Hanley and Tomberlin, 2005). Other than scoring and ranking systems, however, there are few decision support tools currently available to prioritize barriers for removal or mitigation, with the notable exceptions of the optimization and heuristic models described by O'Hanley and Tomberlin (2005). GIS systems could be used to calculate benefits (e.g. river length) versus costs of barrier removal to form an "action plan" that clearly defines priority waters and the migratory obstructions that they contain (Kroes *et al.*, 2006). However, this approach is limited when compared with optimization modelling. Optimization modelling problem formulation or GIS based network analysis systems can be used in the absence of ideal knowledge of the entire fish migration barrier network, and will provide more effective solutions than scoring and ranking systems.

Powerful network models have been developed over many decades for the purpose of planning transport systems. There exists an exciting opportunity to adapt current technology to provide a "state-of-the-art" prioritization tool to meet the requirement of the WFD while minimizing the duplication of development effort. It is highly recommended that this opportunity be pursued. How prioritization mechanisms may be developed that calculate an optimal solution by accommodating information related to population dynamics (e.g., Letcher *et al.*, 2007) and system specific life-history bottlenecks, is an important area for future research.

Although considerations of appropriate prioritization tools have been driven by the need to identify optimal solutions for barrier removal or mitigation, optimization and network analysis models may also be used to calculate the impact of building further structural barriers to fish migration. This is an important consideration and particularly timely considering the increased interest in the development of small-scale hydropower potential throughout the British Isles. These models may, therefore, prove extremely important in their application as planning tools.

The development of a protocol for habitat assessment was outside the remit of this report. However, suitable habitat assessment protocols are an essential component of the methodology. There is a need to adequately define habitat suitability for the relevant life-stages of the target species, and to develop an appropriate protocol to be employed by field survey personnel. For some species, the necessary information for some life-stages may be considered insufficient, and thus drive future research initiatives. The selection of suitable candidates to act as “umbrella” species based on a good understanding of habitat requirements may be justified during the interim.

The considerations of methodologies reviewed and proposed in this report are biased towards restoration of fish populations. However, the overall purpose of restoring habitat connectivity is to enhance Ecological Status or Potential as required under the WFD. In the context of the current project, and the need for the British Isles to develop a strategy to meet obligations defined by the WFD, then a more holistic approach could be adopted in which the requirements of entire ecosystems (and geomorphological processes on which they are based) are considered. For example, a high gradient upland stream may have insignificant value in terms of its potential for fish productivity, but under high flowing erosive conditions, may provide the source of fluvial gravels that sustain important spawning areas further downstream. A barrier that prevents the transport of sediment may not necessarily block the movements of fish, but can impede geomorphological and ecological processes. When considering upstream migrating fish, complete barriers situated close to the estuary have the highest potential impact. From the perspective of sediment supply, however, barriers that block movement of bed load material from the upper tributaries may be the most significant. Consideration of sediment dynamics also has further complicating implications for prioritization. Cost: benefit analysis may assign a low rank to any barrier that has limited suitable habitat for the target species upstream of it. However, if the habitat is unsuitable because the replenishment of sediments is prevented by a further upstream barrier (e.g., in the case of salmonids spawning habitat), then the identification of an optimal solution will be made difficult without values for potential habitat quality improvement as a result of the reinstatement of sediment supply. Ultimately, however, the powerful prioritization models described could accommodate this type of analysis if provided with sufficient information. Nevertheless, the use of fish population status as a proxy measure of ecological status is a valid approach for the initial stages of a long term programme.

Freshwater environments are changing with shifts in climate regime. Fish passage efficiency associated with structural barriers will alter as flow and temperature regimes respond to the changing climate. In the British Isles, average annual temperatures are expected to increase by between 1ºC and 5ºC by 2100 (UKCIP, 2002). As river temperatures track ambient air temperatures, biological processes, including fish swimming performance (Brett and Glass, 1973; Beamish, 1978; Brett and Groves, 1979) and behaviour (Linton *et al.*, 2007), will be affected. At higher temperatures, upstream migration will involve swimming that will tend to be continuous with a constant increase in muscle activity throughout the ascent (Booth *et al.*, 1997). This results in an increase in maximum swimming speed, but decrease in endurance, thus affecting ability to negotiate structural impediments. Average rates of precipitation for the British Isles are expected to change, so that by 2100, winters will be milder and wetter, with 30% higher rainfall, while summers will by hotter and dryer, with 50% less rainfall than present (UKCIP, 2002). The frequency and intensity of low flows during the summer, and high discharge events in the autumn and winter, are expected to increase. This has significant implication for the porosity of some structures to the movement of fish, e.g. culverts that may increasingly maintain insufficient depths of water during low flows, and excessively high velocities that exceed the swimming capabilities during high flows. The effectiveness of river infrastructure to block fish, and fragment habitat, will increase during such events. The proposed methodology may be developed to incorporate climate change predictions to illustrate how barrier porosity will vary with flow and temperature regime. Prioritization analysis could potentially consider current versus future cost: benefit analysis, and calculate different optimal solutions based on time-scale.

It is important to view the development of the proposed methodology as an incremental and iterative process in order to create a robust management tool. It has previously been argued that there exists a severe danger that the

WFD provides a vision without the essential management tools to support it, and as a result, derogation from the technical core of regulatory action will be common, thus endangering freshwater ecosystems rather than safeguarding them (Boscheck, 2006). It is important, therefore, that this initiative is not criticized by some for producing of a weak, hasty or faulty tool, despite a political will towards "strong" sustainability (Newsome, in press). Further, fish passage criteria and understanding of habitat requirements, life histories, and population dynamics are constantly being improved. For example, research is currently being conducted at ICER to assess behavioural response of multiple species of fish to hydraulics and other environmental factors associated with structural impediments. Relevant future information and the results of validation studies must be used to drive improvements in the methodology. As previously mentioned, design of barrier porosity assessment protocols; the construction of an appropriate inventory for the fish migration barrier network; and development of prioritization analysis tools, must take place in a cohesive and integrated manner. The challenge is to achieve this with limited financial resources. It is recommended that a consortium of stakeholders, representing relevant regulatory agencies and authorities; the industrial sector; fisheries and conservation organization; and academic institutions, develop a strategic plan to identify and acquire sources of funding. Further, an international network should be developed in which other agencies that are currently developing their own methodologies and tools to meet the objectives defined in this report (e.g., in North America and Europe) are invited to participate. This will reduce potential for costly duplication of effort and provide added value for all participants.

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