Title: An integrated decision driven design framework to support the ecological restoration of rivers

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Abstract

A structured and collaborative approach to design and decision-making in the context of ecological restoration of rivers is developed and illustrated using a case study involving the mitigation of physical barriers to fish migration on the River Trent in the UK. The integrated design and decision-making framework provide a practical workflow model for structuring multi-attribute decisions, engaging stakeholders, and assembling a design team needed to successfully plan environmental interventions. In our implementation team members included ecologists, fisheries biologists, government scientists, and representatives of key stakeholder groups. The case study demonstrated a values-based approach to implementing an ecological restoration plan that addresses some of the long-standing barrier removal goals associated with the reintroduction of Atlantic salmon and European Union (EU) Habitats Directive listed species European lamprey and River eel. The integrated decision-driven, design framework approach is highlighted by trans-disciplinarily and social learning.

Keywords: River rehabilitation, catchment approach, Decision framework, Habitat improvement, river connectivity

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1. Introduction

Despite considerable investment in river restoration to improve degraded habitats since the late 1980s, there is limited information on the efficacy and success of river restoration activities (Bernhardt et al., 2005; Roni et al., 2008; Roni and Beechie, 2013). Angelopoulos et al. (2017) reviewed 671 European river restoration case studies and found only 9% could determine ecological success, 1% reported failure, whereas the outcome of 90% of case studies were either unclear or no information was reported. Further investigation concluded that poor or improper multidisciplinary project planning, monitoring, and evaluation limits a manager's ability to detect change from restoration activities (Angelopoulos et al., 2017). Similar findings have been reported in industrialized countries (Bernhardt and Palmer, 2005; Boon and Raven, 2012; Roni and Beechie, 2013; Palmer et al., 2014; Friberg et al., 2016). Even though our understanding of river restoration has improved, advances in planning and application, and determining change and project success are still lacking. Sequentially, this leads to a systematic breakdown in appropriate decision-making, including failure to set clear, measurable outcomes, not addressing the root cause of habitat degradation at the appropriate scale, and failing to address rivers as dynamic systems with natural spatial and temporal variation that influence physical and biological diversity. An integrated systems view that gives attention to both the values of stakeholders and scientific information concerning the potential consequences of alternative restoration actions is required. An explicit, value-laden, decision-driven approach based on the best available information is required that links values to facts (Gregory et al. 2012).

The river basin planning environment is characterized by competing stakeholder values, conflicting data requirements and metrics, varying spatial and temporal scales, and incomplete knowledge systems. Multiple frameworks have been described to aid in managing these types of complex socio-ecological systems (Angelopoulos et al., 2017; Binder and McDonald, 2007; Eddy et al., 2014; Hammond et al., 2011; Roni and Beechie, 2013). In addition, authors have described approaches to environmental systems analysis by developing general but reproducible decision-making frameworks (e.g., Gregory et al. 2012; Skidmore et al. 2011). Despite these advances, none of these framework approaches incorporate dynamic spatial modelling, decision-making processes or scenario creation that integrates digital technology to enable the live testing of river restoration plans in workshop environments with stakeholders. An integrated systems view that gives attention to both the values of stakeholders and scientific information concerning the potential consequences of restoration actions is required; one that is explicitly value-laden and decision-driven based on the best available information that can link values to facts (Gregory et al., 2012).

Taking into account these imperatives, this paper develops a structured and collaborative approach to design and decision-making for river restoration projects. To accomplish this, the Geodesign framework (Steinitz, 2012) was integrated with key elements from Structured Decision Making (SDM) (Gregory et al., 2012). Geodesign is at the forefront (Li and Milburn, 2016) of these applications and is a design and planning methodology that tightly couples the creation of a design proposal with impact simulations informed by geographic context (Steinitz, 2012; McMillan-Wilhoit et al., 2018). SDM is an approach that allows careful and organized analysis of natural resource management decisions. Based in decision theory and risk analysis, SDM encompasses a simple set of tools and concepts and helpful steps, rather than a rigidly-prescribed approach for problem solving (Gregory et al. 2012). The result of the integration of these two approaches is a river restoration planning and analysis tool (RRPAT). RRPAT is designed will allow for more consistent and thorough planning and evaluation of the potential effects of proposed restoration plans on river values. It is anticipated that wider adoption of such an approach could help to ensure project planning and evaluation of river restoration initiatives are effective, transparent, and repeatable.

The objective of the RRPAT tool is to enable scientists, managers, and local watershed stakeholders to; (1) understand better the connections between physical processes and aquatic habitat; (2) acknowledge and understand the connections between representative data, river processes, evaluation of key attributes, change scenarios, impacts of change, and trade-off and decision-making in the planning and design process; (3) become aware of restoration design alternatives that can minimize risks to species and habitat; (4) provide project monitoring and evaluation, and foster consistent reporting; and (5) promote best practices for effective future river management. To demonstrate the utility of RRPAT, it is applied to a comprehensive case study on the River Trent, UK. The case study is used to examine the application of the tool to optimize barrier removal scenarios associated with the reintroduction of Atlantic salmon (*Salmo salar* L.) and European Union (EU) Habitats Directive listed species river lamprey (*Lampetra fluviatilis* (L.)) and eel (*Anguilla 4nguilla* (L.)).

2. The General Geodesign Framework

The general framework (Fig. 1) follows Steinitz (2012) and poses six key questions in three successive iterations through six modelling steps. The three main iterations comprise scoping the problem, design and implementation. The six key questions are asked in an alternating sequence. The first question asks how the river should be described with respect to content, space and time. Representation models are used to answer this question and present the essential data (i.e., content, space and time) that underpin the study. The second question asks how does the river basin function or what are the functional and structural relationships among its elements. This question is answered by process models, which provide information for the series of assessments that are required by the study. The third question asks if the current system functions well. This question is answered by evaluation models, which are dependent upon knowledge of the stakeholders. The fourth question asks how the river basin might be improved. This can be addressed by identifying and setting the actions in a temporal and spatial context. Change models are then used to develop and compare alternative restoration scenarios. These models also generate data that can be used to forecast alternative future states. The fifth question asks what differences the proposed changes might cause; this question is answered by impact models that are assessments produced by the process models under changing conditions. Last, the sixth question asks how the river basin should be changed; this question is answered by decision models that, like the evaluation models, depend on the local and/or cultural knowledge of the stakeholders involved. The first three steps in the process define the assessment phase, and the last three stages define the options for intervention.

INSERT Fig. 1. General Geodesign Framework (Adapted from (Steinitz, 2012))

3. Structured Decision-Making (SDM) Approach

A Structured Decision-Making (SDM) framework (Fig. 2) provides a methodical and transparent way to integrate values and objectives from multiple decision makers and stakeholders into the decision-making process (Gregory et al., 2012). The SDM framework follows six steps that help organize the decision-making process. The first step is designed to scope the problem and sketch the decision context. This step includes clearly defining the decision context that identifies the primary management objectives, the broadly defined manner in which the problem will be addressed, the spatial and temporal boundaries, and the roles of different parties in the process. The second step is to identify objectives. They are defined as both fundamental and means objectives. Fundamental objectives are ecosystem and socio-economic aspects that are valued by managers or stakeholders and are typically the focus of management decisions. Means objectives are important because they may help achieve a fundamental objective. The third step is to identify management alternatives that can be taken to manage river values and attributes and achieve the fundamental objectives. The fourth step is to estimate the consequences (i.e., risk and uncertainty) of alternative management actions on objectives. The fifth step is to trade off and choose the best alternative for implementation. The sixth step is implementation of the plan – which includes monitoring, evaluation and reporting. It is critical to note that the SDM process and model outputs do not make decisions for managers but rather provide input that can help inform decisions. The process is also iterative and provides feedback on the success and failure of decisions.

INSERT Fig. 2. Six step process of the Structured Decision Making (SDM) (adapted from (Gregory et al. 2012))

4. Integration of the Framework for Geodesign and SDM

The systematic application of the tool incorporating river restoration was developed according to the process informed by Steinitz's framework for Geodesign and structured decision-making (Fig. 3). The integrated framework is represented by a multi-step workflow. The workflow can be easily applied to any restoration project under a variety of information conditions. Using the structured decision-making workflow and integration into the Geodesign framework allows effective organization of key aspects of the process, the contribution of the stakeholders within the different phases, and the use of appropriate facilitation techniques – ideally using a workshop environment. Stakeholder participation plays an important role in the process, helping to integrate local and expert knowledge of the river and therefore informing the design. The integrated framework comprises 19 steps in 3 iterations of Geodesign. The work flow is colour-coded to integrate the 6 steps of SDM (from Fig. 2) explicitly in the framework (from Fig. 1). Each step is described in detail and a suite of tools and techniques are associated with each step. Typically, when applying the framework, the first step is to provide a brief lecture to the participants introducing SDM and the Geodesign concepts and principles, the Steinitz' framework, the problem and the study area, and the GIS / digital approach. Workshop participants then move through the framework step by step as described in Figure 3 and depicted as spatial information flows for each iteration as described in Figures 4-6. Through the three iterations, participants add detailed descriptions of the datasets and models and associated tools. The data, models and tools are then used to assist in the development of a final course of action.

INSERT Fig. 3. River restoration planning and analysis tool workflow for river restoration projects

Iteration one (Fig. 4) develops a collective awareness and understanding of the study area and the scope of the problem(s) being addressed. In this iteration, the questions are posed as 'why' questions. The iteration is designed to build an understanding of the specific problems, issues, considerations, constraints in the study area, objectives of the project, and the relevant context and scales of possible change (Steinitz, 2012). In addition, the design team identifies possible changes and impacts. The first steps in the design process must address choices and make decisions to define the scope of the project, the potential methods, and identify the predicted outcomes. This initial sketching of the decision is the primary focus of the first iteration. Prior to scoping potential logical paths from representative data to final decision, proponents can map the key ecosystem elements and processes in the decision environment thus helping to identify all key participants (i.e., stakeholder values that are present) and any existing legal, regulatory, societal or political constraints in the decision environment that must be considered (i.e., boundaries and scope). This stage clarifies the decision context. At this point all the available data are identified, and the dynamics of the systems are characterized. A variety of tools can be used to provide an integrated systems view. Scoping defines why things are going on and what is valued. This integrated view allows environmental drivers to be linked: representative data to process, process to values, value to change and impact, and ultimately the linkage to decision. The design team can thus create a mental map of the environment in which the decision is being made. Setting objectives and ascribing measurable values to key ecosystem components renders the process decision to not being data driven. At this early stage of scoping, it is critical to take the design process as far as possible to provide preliminary development of potential alternative solutions. The decision environment can be more formally defined and structured with several approaches or tools incorporated (i.e., science to values assessment, strategy tables portfolio builder, brain storm, consequence tables (Gregory et al. 2012).

INSERT Fig. 4. Iteration 1 of RRPAT depicted as a spatial flow with associated questions and requirements

Iteration two (Fig. 5) establishes the project design. Specifically, to choose and clearly define the method of the study, the 'how' questions. The questions are posed in reverse order (i.e., 6 to 1). The reversal of the question allows the design team to define the methods to be used in the study, and consequently design becomes decision driven, not data driven (Steinitz, 2012). At this stage, it is important to focus and define the decision. Critical to this iteration is to define the potential impacts that are to be considered. Once the priorities are established, the design team can outline the means or strategy by which they will create change. In addition, they will decide how to assess existing conditions and investigate the structural and functional processes of the river of study and specify appropriate methods and data requirements. The requirements for data acquisition and appropriate means of representation are also identified. Once the scoping exercise is complete, the team moves on to the core design part of the workshop.

INSERT Fig. 5. Iteration 2 of RRPAT depicting the method of design, information flow with questions.

The design team chooses a method to prioritize impacts and defines the specific models that forecast the impact of change scenarios. It is critical that the model forecast identifies the consequences in terms of risks and uncertainty to allow for relative comparison, and enable trade off between alternatives with the team. At this stage, methods to visualize the dynamic processes are required. Ideally model outputs should be systematically organized in the matrix, making them available for use by all the participants. Once all models are in place, running the various scenarios can occur.

In iteration three (Fig. 6) the design team implements the methodology designed in the second iteration. Central to this iteration are the `what', 'where' and 'when' questions the team pose, which allows the team to begin implementation. In this phase, the questions are asked in forward sequence (i.e., 1 to 6). During this iteration, data become the central focus. The design team now identifies and gathers the specific data necessary for the study, organizes the data with an appropriate technology and represents them in a format useful for the study purposes. Once the relevant data are organized for the process models, the resulting information is used to develop a baseline from which assessments of both the existing study area and the impacts of future changes are made. The potential range of future alternative states of the study area are then compared. Decision-makers can then better understand the potential consequences, risks and uncertainty of alternative actions and begin the process of trading off between alternatives. This leads to three possible decisions – 'no', 'yes' or 'maybe'. If the answer is 'no' or 'maybe', and the design does not meet the established requirements or there is uncertainty among the decision makers, then all or some of the six steps can revisited and alterations made. At any point in the process, additional information can be added and decisions revisited.

INSERT Fig. 6. Iteration 3 of RRPAT as a generic process

5. Case Study

Case study selection and rational: The tool development is supported by empirical data from a comprehensive synthesis of a large river case study in the UK. The case is focused on the optimization of accessible habitat for Atlantic salmon (*Salmo salar* L.), European eel (*Anguilla 9nguilla* (L.)) and the River lamprey (*Lampetra fluviatilis* L.) on the River Trent in the UK (Fig. 1). This river case study was selected because of a rich data environment providing the opportunity to demonstrate the full utility of the RRPAT framework to river restoration planning and design. The case study data comes from original studies by Nunn and Cowx (2012).

Pre-workshop Planning: Case study preparation started in January 2019. The scoping phase was carried out by the authors in conjunction with subject matter experts. The pre-workshop planning phase included several face-to-face workshops, Skype meetings, and email communications. The knowledge base for the case-based scenarios was developed using the expert group approach.

The Participants: Six design team members were identified. The team came from a variety of backgrounds spanning from fish ecology, habitat management, ecological restoration, GIS science and information technology (IT), creating a good mix of competencies for a Geodesign study. In addition to the design team, each barrier in the case study was evaluated by a group of twelve experts regarding all evaluation criteria (Nunn and Cowx, 2012). The participants had previous personal knowledge of the local context of the case, having studied the data and performed extensive field visits to the region. The expert group combined to create a multi-disciplinary team, each member playing the role of a different stakeholder group with various interests to simulate and assess potential futures for both river systems.

5.1 Design Workshop

Iteration 1:

Scoping of this case study used reports, existing maps and spatial data, and field-based examination of barriers in the Humber basin and tidal River Trent, England (Cowx and O'Grady, 1995) and an expert workshop on potential for hydropower are barriers throughout the catchment (Nunn et al., 2012). The Trent is the largest river in the Humber basin (280 km long, 10,500 km^2 catchment area) (Fig. 6).

INSERT Fig. 7. Map of the Humber basin and the location of case study barrier on the River Trent, UK

A major problem in the River Trent concerns migratory fish populations, which have been heavily impacted by extensive modifications of the river through flow regulation projects, construction of artificial barriers, channel modification and water quality (Cowx and O'Grady, 1995; Nunn and Cowx, 2012). The extensive industrial development of the basin has resulted in many potential barriers to fish migration (Nunn and Cowx, 2012). Weirs, sluices and barrages in the system act as obstructions preventing migrating fish accessing critical spawning and rearing habitats, thus affecting distribution and population structures, and impacting on spawning success and recruitment of fish (Baras and Lucas, 2001; Nunn et al., 2008, 2010; Nunn and Cowx, 2012). For this case study, seven potential barriers to the longitudinal migration of diadromous fish species in the mainstream lower reaches of the River Trent were identified and assessed (Fig 6). To facilitate fish migration, an understanding of the types, characteristics and impacts of barriers to fish migration is crucial. Barriers have been connected to population declines in diadromous species (Baras and Lucas, 2001; Limburg and Waldman, 2009; Renaud, 1997; White and Knights, 1997). Even a delay in the regular migration could increase the risk of predation, stress and disease (Gargan et al., 2011). This understanding is necessary if we are to optimise the use of resources and achieve the best possible outcomes. Specifically, the case study targets improving fish passage to optimize access to critical habitat for three species; Atlantic salmon, European eel, and river lamprey. Critical habitat for these species has been well-studied (Christoffersen et al., 2018; Degerman et al., 2019; Gibson, 2002; Harvey and Cowx, 2002; Lucas et al., 2009; Maitland 2003; Moir et al., 2006; Nunn et al., 2007) and is identifiable by the experts. Critically the initial studies used historical and recent studies on the distribution of the three species in the catchment based on library archives and fisheries surveys carried out by the Environment Agency and its predecessors. The suitability of the habitat was also assessed for its importance to fish community dynamics using the fish-based approaches to assessing the ecological health of the river reaches in question (Noble et al. 2007a, b; Reyjol et al. (2007). The loss of habitat was found to be directly linked with the loss of longitudinal connectivity, an enormous threat known to stem from anthropogenic barriers (Cote et al., 2009; Radinger et al., 2017, 2018).

Improvements in fish passage will involve the prioritization of barriers for installation of fish passes (to increase longitudinal connectivity). Optimizing the decision will be constrained by available resources, which limit barrier improvement activities to a choice of any two barriers of the seven under investigation on the River Trent.

Iteration 2:

*Decision Model***:** The decision model is based on the outputs of impact models that define the degree of change between the baseline (current state) and a future alternative state expressed as a change in total accessible habitat for each target species. Accessible habitat will have some net gain of habitat quantity and quality for Atlantic salmon, European eel, and river lamprey as defined by Hendry and Cragg-Hine (2003), Nunn et al. (2007) and Maitland (2003), respectively. The total positive change in accessible target habitat area is weighed by quality and further constrained by annual limit on the number of barriers to be removed by limitations on financial resources. This allows for a realistic setting of annual and longer-term sequential restoration objectives. The nature of the decision requires a trading off of potential alternatives based on the consequences and impact of different restoration plans. There are three potential decision alternatives in this case study; 1) maximize salmon habitat, 2) maximize European eel habitat, and 3) maximize river lamprey habitat. The fundamental objective is to maximize habitat for each species under a minimized cost condition. The most optimal combination of barriers for passage improvement will be determined for the river for all three objectives. The most effective decision model for this scenario is a Multiple Attribute Decision Matrix (MADM), which can show the relative impact of change scenarios on all evaluation criteria across all three objectives. The MADM model evaluates the magnitude of the change caused by restoration treatments with respect to change in accessible habitat of varying quality for the different species and the likelihood of access.

Impact Model: To describe the potential impact of anticipated changes, it is necessary to provide an initial ranking of barriers based on an expert assessment. Prioritization is based on an initial scoring and ranking of several key criteria that define a composite barrier score. These criteria include status of the fish stock, habitat quality and quantity above the barrier, passage efficiency and likelihood of access. At this stage, spatial relationships of barriers are not included, hence removal decisions are independent of one another. To choose an optimal set of barriers it is necessary to describe the barriers spatially. The spatial location of barriers plays a major role in determining factors such as fish dispersion and fish habitat colonization (Radinger et al., 2017; Radinger and Wolter, 2015). Therefore, it is necessary to translate these values and the location of the barriers in the river network with GIS analysis. Point data are used to represent the barriers, and are location-verified against satellite imagery. Topographical waterbody polygon data for United Kingdom National Ordnance Survey grid sections SE and SK were downloaded for coverage of the study area. The river data were also verified against satellite imagery to ensure a perfect match up with the meandering river boundary. The seven river sections were linked up with seven access-controlling barriers (see Fig. 6). In preparation for analysis, the river section beyond a barrier was clipped and separated up to the next barrier. Consequently, each barrier was spatially linked to an amount of potential fish habitat whose access was dependent on the condition of the same barrier. Area calculations were then made for each river section and linked with the controlling barrier. The analysis was contained to main river sections only, and smaller river linked areas such as tributaries or off channel wetlands were removed. All sections were treated as single pathway flows, and were converted to a single pathway if necessary, to remove the complexities involved for multiple pathway barrier conditions. The spatial position of the barrier allowed the calculation of cumulative effects of change in passage efficiency and subsequent changes in likelihood of access across all possible removal combinations, thus optimizing net gain in habitat area and quality.

The assessment of stream fish passage was completed by defining fish passage efficiency as a habitat weighted cumulative value. To calculate values, we created a generalized network model. These points are also called nodes or vertices, and lines are designated as edges. For the purpose of our analysis, a river network (McKay et al., 2013) was constructed with nodes at locations along the longitudinal dimension where conditions change (i.e., tributary junctions, barriers, other pertinent watershed locations) and edges as habitat between these nodes (e.g., length of river between dams). This parameterization was chosen to suit the case study problem. All nodes in a river network were assigned barrier passage efficiency. The focus of this case study for demonstration purposes is upstream habitat connectivity, therefore only upstream passage rates are applied. Habitat connectivity plays a central role in the development of aquatic communities (Cote et al., 2009). We examined diadromous life history whereby a species is migrating upstream from the mouth of the basin. The cumulative passage efficiency is then multiplied by the area of different types of habitat quality. Monte Carlo simulation was run for all possible combinations for passage improvement. The result of the simulation is a histogram showing relative change in total accessible habitat for each target species for all scenarios. The impact model is displayed as an impact map showing the relative difference between each alterative management scenario. The difference is expressed as a net gain or loss in accessible habitat for each target species and as a total for all species; this can be expressed visually using MADM.

Change Model: The choice of which barrier to remove is defined by passage improvement. Each structure is scored on a scale of 1 (smallest potential benefits following passage improvements) to 5 (greatest potential benefits following passage improvements) for the following parameters: (1) ‘Fish stock status’; (2) ‘Passage efficiency’; (3) ‘Likelihood of access’; (4) ‘Habitat quantity’;

and (5) ‘Habitat quality’. All the parameters were scored on the same scale to ensure that each was given equal weight in the prioritization process. The simple prioritization model is defined as:

$$B = F \times P \times A \times H_{\mathrm{qn}} \times H_{\mathrm{ql}}$$

where F was the ‘Fish stock status’, P was the ‘Passage efficiency’, A was the ‘Likelihood of access’, H_{qn} was the ‘Habitat quantity’ and H_{ql} was the ‘Habitat quality’. B ranges from 1 ($1 \times 1 \times 1 \times 1 \times 1$) to 3125 ($5 \times 5 \times 5 \times 5 \times 5$). The structures can then be ranked according to B, identifying priority barriers for passage improvements (priority barriers had the highest B). Nunn and Cowx (2012) noted that the class boundaries for F, A and H_{qn} can be adjusted (standardised against the maximum value in the study) to suit species (e.g., rare vs. common) or study areas (e.g., small vs. large catchments, low vs. high productivity), ensuring that there are no redundant classes in the metrics.

Process Models: The effect of all processes in the system on representative data were interpreted through expert opinion. Expert opinion was used to transform representative data into evaluation criteria. The raw data used to describe all evaluation parameters (F, P, A, H_{qn}, H_{ql}) were collected with a standardized methodology (Cowx and O’Grady, 1995; Nunn and Cowx, 2012). Stock status in this case was based on known distributions of the target species in the impacted reaches based on Environment Agency data, now held centrally in the National Fisheries Population Database[1]. Each barrier was assessed for each species using empirical data (e.g., from surveys as carried out in the current exercise [F, H_{ql}], maps/GIS software [H_{qn}] or existing tools [P, A; see Kemp and O’Hanley (2010)]); if no empirical data were available, ‘expert judgement’ was used based on site visits (Nunn and Cowx, 2012).

Evaluation Models: Evaluation models were matrices represented by ranges of values from the observed raw data expressed as a categorical description of condition and associated with a nominal score. Nominal scores are on a scale of 1 (smallest potential benefits following passage improvements) to 5 (greatest potential benefits following passage improvements) for the following parameters: (1) “Fish stock status”; (2) “Passage efficiency”; (3) “Likelihood of

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[1] https://data.gov.uk/dataset/d129b21c-9e59-4913-91d2-82faef1862dd/nfpd-freshwater-fish-survey-relational-datasets

access”; (4) “Habitat quantity”; and (5) “Habitat quality”. All the parameters are scored on the same scale to ensure that each is given equal weight in the change model (Prioritization Model) (B). Each value was assessed for each barrier by a group of 12 experts in the original study (Nunn and Cowx, 2012).

Fish stock status (F) is defined as the status of the stock of the target species (diadromous fishes or lampreys) upstream of each structure, up to the next structure, with the poorest stocks scoring highest (Table 1). Note that “Fish stock status” refers to the ‘non-migratory’ life periods of the target species that inhabit rivers (e.g., fry and juvenile Atlantic salmon, juvenile European eel, ammocete river lamprey).

Passage efficiency (P) is an estimate of the percentage of the target species that successfully passes individual structures (in normal flow conditions during the migration period), with the lowest efficiencies scoring highest (1 = >95, 2 = 66-95, 3 = 36-65, 4 = 6-35, 5 = ≤5% passage efficiency).

INSERT Table 1. Determination of “Fish stock status” for Atlantic salmon, European eel and river lamprey

Likelihood of access (A) is an estimate of the difficulty of passage by the target species upstream to each structure; a function of the distance from the tidal limit and the passage efficiency at downstream barriers, where the latter is a product of the individual passage efficiencies at downstream barriers (e.g., 25% × 80% × 100% × 50% = 10%), with the easiest passages scoring highest (Table 2). Note that the “Likelihood of access” score of a particular structure will necessarily be lower than those of any barriers downstream.

INSERT Table 2. Determination of “Likelihood of access”

Habitat quantity (H_{qn}) is an estimate of the quantity (river length, including tributaries if appropriate) of habitat upstream of each structure, up to the next structure, with the greatest quantities of habitat scoring highest (Table 3).

INSERT Table 3. Determination of "Habitat quantity"

Habitat quality (H_{ql}) is an estimate of the quality of habitat upstream of each structure, up to the next structure; a function of water quality and physical habitat characteristics, with the highest quality habitats scoring highest (Table 4). Note that "Habitat quality" refers to the requirements of the life period of the target species that migrates into rivers (e.g., spawning habitat for adult Atlantic salmon and river lamprey, nursery habitat for juvenile European eel, as indicated in studies such as Hendry and Cragg-Hine (2003), Nunn et al. (2007), Maitland (2003) and van Zyll de Jong & Cowx (2016).

INSERT Table 4. Determination of "Habitat quality"

Representation Models: 67 potential barriers (mostly weirs) to the longitudinal migration of Atlantic salmon, European eel and river lamprey in the Humber basin were assessed and an additional 18 potential barriers (mostly weirs) were surveyed in the River Trent between Cromwell Weir (tidal limit) and the Colwich (near Stafford). General information for each structure (e.g., structure name, type and purpose, catchment, watercourse, latitude and longitude, channel width, upstream land use, distance from tidal limit) was collated in a spreadsheet. In addition, evaluation matrices for expert assessment / evaluation were completed. Fish density for each target species is expressed as number per area; Passability was expressed as the percentage pass rate for species; water quality and physical habitat character for rearing and spawning life stage is quantified and length of stream is listed. Process matrices used these data to produce evaluation criteria.

Iteration 3:

Representative, Process and Evaluation models: Representative data for all barriers were presented including B-value data for each case (Table 5). The representative data provided a range of observed values to create matrices for nominal scale qualitative characterization for expert judgement. The case study shows the result for one river section of the River Trent for demonstration purpose.

INSERT Fig. 8. A fully populated RRPAT Design for case study modelling for barrier mitigation on the River Trent, UK

Change Model: The design team ran the scenario for seven barriers along the river section for the three species of concern. All possible combinations of barrier passage improvements for three change scenarios were run, viz. (1) maximize Atlantic salmon habitat, (2) maximize lamprey habitat, and to (3) maximize European eel habitat.

INSERT Table 5. Values for each barrier for 3 species of concern. B = total barrier score, F= fish stock status; P = passage efficiency; A = likelihood of access; H_{qn} *= habitat quantity;* H_{ql} *= habitat quality*

Impact Model: For the purposes of the case study, the impact models are displayed as a resulting histogram showing the cumulative percentage change in accessible quality habitat for all possible combinations of barrier removal for each species.

INSERT Fig. 9. Histograms depicting the total change in accessible habitat for each habitat class by species for all 21 combinations of sets of 2 for removal

The case study analysis examined seven sequential barriers on the River Trent, each restricting migratory access to sections of significant habitat for salmon, eel and lamprey. The design team ranked habitat quantity and quality for all sections through expert judgement. Expert knowledge used in this manner is dependable and well-known (see for example Lucas et al. (2009), Moir et al. (2006), and also Christoffersen et al. (2018)). The various combinations of barrier restoration from current expert rated passability ratings to highest possible passability rating (i.e., to 0.975 passability) were reviewed for each habitat quality class. Figure 9 shows the percentage increase in the quantity of two classes of habitat quality (class 3 and 4) for all three species of concern. Maximum salmon habitat gain is achieved by the removal of barrier combination 1-4 or barrier 4-5 for class 3, with an increase of 94% in each scenario. Maximum lamprey habitat gain would be the removal of 1-4 combination increasing class 3 lamprey habitat by 142%. Eel is not present in the class 3 improvements results. Maximal increase to class 4 habitat quality for salmon would be the removal of barrier combination 1-4, for lamprey 1-4 and for eel any combination that includes barrier 7. The team also examined the minimum number of barriers to get the highest cumulative effect for all 3 species as trade off becomes necessary (Table 6). The top two barriers that produced the maximum habitat gain cumulatively for all three species were identified. The optimal set of barriers to achieve increase in all three species was barrier set 1 and 7.

It is important to note that when comparing the output of the impact model simulation and the traditional site-specific classification of barriers with a total B value, the result is very different. The B scores (Table 5) would suggest the removal of barriers 1 and 2 to achieve maximum gain for all species, but when the data are modelled and simulated the maximum gain is achieved by removing barriers 1 and 7. This finding underscores the importance of examining the causal relationship between process, change and impact when exploring the development of alternative actions and forecasting the potential consequences of proposed actions. This ability to forecasting is critical to the creation of meaningful alternatives, and enables stakeholders and decision makers to evaluate trade-offs in an open, pluralistic and transparent social learning environment.

*Decision Model***:** When the first round of synthesis is completed, each scenario in its first version was evaluated. The visualization tool MADM platform provided an interactive impact assessments dashboard to compare the impacts of different scenarios after the first iteration. The users can rapidly drop/add change options or modify/create diagrams until they are satisfied with the impact performance of their design through subsequent iterations.

INSERT Fig. 10. A multi-attribute matrix showing the relative percentage change for each species by habitat class and the cumulative increase for all species. Values are shown as a histogram (relative percentage increase) and a map showing the location and magnitude of the change for the top sets of barrier removals

In addition to the use of the MADM platform a consequence table (Table 6) was used to evaluate scenario providing a basis for trade-off between the species under the two-barrier mitigation constraint. Alternative 1-7 provides the greatest increase in all species cumulatively and provides maximum for all 3 species. Alternative 1-7 is chosen as the best alternative scenario to optimize Atlantic salmon reintroduction while protecting EU Habitats Directive listed species European lamprey and European eel.

INSERT Table 6. Trade-off consequence table of choice of barriers combination on fish habitat

6. Discussion

The general rationale for the development of the river restoration planning analysis tool was to support scientists, river management, and local watershed stakeholders to make better informed and structured decisions. The framework developed in this paper provides explicit guidance describing the integration of necessary design and decision-making elements to improve decision outcomes. The connection between fundamental objectives, which are represented by information (i.e., performance measures), were linked using process models to allow for measurable changes in target species habitats, and this was a fundamental element. The causal relationship between process, change and impact is fundamental for exploring the development of alternative actions and forecasting the potential consequences of proposed actions. This ability to provide forecasting is critical to the creation of meaningful alternatives and enables stakeholders and decision makers to evaluate trade-offs in an open, pluralistic and transparent social learning environment. The consistent use of the framework will lead to standard project identification, project preparation, project implementation, monitoring and evaluation. Bringing such a standard practice to river restoration decision-making and project evaluation will allow groups to share best practice. It is anticipated that applying this standard approach will build an inventory of projects and data that will help advance the science of ecological restoration and improve interventions.

The framework extended the use of Geodesign and Structured Decision Making in river restoration. The application of the RRPAT to the case study will encourage more scholars and practitioners to integrate restoration with systems thinking. The RRPAT is a framework that guides a potential practitioner through systemic processes and comprehensive interconnections between human and environmental systems. Such a tool provides a method to explore complex social-ecological process and system dynamics to achieve better results that are more effective. In contrast to site-specific design solutions, this framework provides a systematic approach that can be used at multiple scales both spatially and temporally. The case study approach demonstrates and improves our ability to understand the connections between physical processes and aquatic habitat at varying scales, thus, creating a greater understanding of the connection between restoration efforts, effects, and associated risks and uncertainty to fish species and their habitat. The explicit incorporation of prediction and forecasting to all potential restoration alternative actions helps to mitigate risks to protected species and habitat. The knowledge created provides the utility to document and streamline project planning, implementation and review, and foster consistency in evaluation and monitoring procedures, as well as promoting effective post-project appraisals, leading to more effective future river restoration efforts.

The case study highlighted three target species habitats, or in ‘decision-making ‘language’ three values. This simple case was used to demonstrate the utility of the RRPAT framework. In addition, representative data were applied to an expert’s judgement to create a nominal classification system that allowed for the description and ranking or evaluation of barriers. This approach to construct values to measure performance is subjective, but with further iterations of the tool in data rich environments, the development of a variety of quantitative approaches to process and prediction are realistic. This framework presented in this paper invites future scholars, designers and planners to look beyond the boundaries of the project and embed Geodesign and SDM approaches and systems’ elements into multi-scale, multi-level, nested human-environment systems. The RRPAT approach provides guidance about how to use an integrated design and decision-making process with ecological systems at multiple scales and dimensions, rather than individual design ideas for specific sites. Furthermore, it invites managers to identify social-ecological and spatial-temporal dimensions to restoration challenges. In the field of policy, especially environmental policy, policy analysts can use this tool to study existing interventions and their relations with coupled social-ecological systems to prevent dangerous combinations of policies across scales. Future research should continue to co-opt ideas and approaches from other disciplines for improved planning purposes.

Despite identifying a comprehensive tool for river restoration that allows for consistent planning, implementation, evaluation and monitoring, gaps and challenges still exist to realize the tool’s full potential. From a theoretical perspective, operationalizing the tool is challenging because it involves complex systems and dynamic processes that require refined modelling processes. Practically speaking, the tool acts as a catalyst for collaboration between scientists, experts and non-experts, but coping with the varying needs to display information is an ongoing challenge. This paper attempts to define a better planning and analysis framework that can provide a systematic method for all practitioners to properly scope, analyse, design, implement and report results properly. Further technological development is the next challenge for design teams. Further research and development will more fully integrate tool kits with advances in modern technologies.

References

Angelopoulos, N. V., Cowx, I. G., & Buijse, A. D. (2017). Integrated planning framework for successful river restoration projects: upscaling lessons learnt from European case studies. *Environmental Science & Policy*, *76*, 12-22.

Baras, E., & Lucas, M. C. (2001). Impacts of man's modifications of river hydrology on the migration of freshwater fishes: a mechanistic perspective. *International Journal of Ecohydrology and Hydrobiology*, *3*(01).

Bernhardt, E. S., & Palmer, M. A. (2007). Restoring streams in an urbanizing world. *Freshwater Biology*, *52*(4), 738-751.

Bernhardt, E. S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Powell, B., & Sudduth, E. (2005). Ecology. Synthesizing U.S. river restoration efforts. *Science (American Association for the Advancement of Science)*, 308(5722), 636-637.

Binder, T. R., & McDonald, D. G. (2007). Is there a role for vision in the behaviour of sea lampreys (Petromyzon marinus) during their upstream spawning migration? *Canadian Journal of Fisheries and Aquatic Sciences*, *64*(10), 1403-1412.

Boon, P., & Raven, P. (Eds.). (2012). *River conservation and management*. John Wiley & Sons.

Christoffersen, M., Svendsen, J.C., Kuhn, J.A., Nielsen, A., Martjanova, A., & Støttrup, J.G. (2018). Benthic habitat selection in juvenile European eel *Anguilla 21nguilla*: Implications for coastal habitat management and restoration. *Journal of Fish Biology*, 93(5), 996-999.

Cote, D., Kehler, D., Bourne, C., & Wiersma, Y. (2009). A new measure of longitudinal connectivity for stream networks. *Landscape Ecology*, 24(1), 101-113.

Cowx, I. G. & O'Grady, K. (1995). The reintroduction of salmon in the River Dove via the River Trent. Report to the National Rivers Authority. National Rivers Authority, Nottingham.

Degerman, E., Tamario, C., Watz, J., Nilsson, P.A., & Calles, O. (2019). Occurrence and habitat use of European eel (*Anguilla 22nguilla*) in running waters: Lessons for improved monitoring, habitat restoration and stocking. *Aquatic Ecology*, 53(4), 639-650.

Eddy, B. G., Hearn, B., Luther, J.E., van Zyll de Jong, M., Bowers, W., Parsons, R., Piercey, D., Strickland, G. & Wheeler, B. (2014). An information ecology approach to science–policy integration in adaptive management of social-ecological systems. *Ecology and Society* 19(3): 40. Doi:10.5751/ES-06752-190340.

Friberg, N., Angelopoulos, N.V., Buijse, A.D., Cowx, I.G., Kail, J., Moe, T.F., Moir, H., O'Hare, M.T., Verdonschot, P.F.M., and Wolter, C. (2016). Effective river restoration in the 21st century: from trial and error to novel evidence-based approaches. *Advances in Ecological Research* 55, 535-611.

Gargan, P. G, Roche, W. K, Keane, S, King, J. J, Cullagh, A, Mills, P, & O' Keeffe, J. (2011). Comparison of field- and GIS-based assessments of barriers to Atlantic salmon migration: A case study in the Nore Catchment, Republic of Ireland. *Journal of Applied Ichthyology*, 27, 66-72.

Gibson, R. J. (2002). The effects of fluvial processes and habitat heterogeneity on distribution, growth and densities of juvenile Atlantic salmon (Salmo salar L.), with consequences on abundance of the adult fish. *Ecology of Freshwater Fish*, 11(4), 207-222.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., & Ohlson, D. (2012). *Structured decision making: a practical guide to environmental management choices*. Wiley, Oxford.

Hammond, D., Mant, J., Holloway, J., Elbourne, N., & Janes, M. (2011). Practical river restoration appraisal guidance for monitoring options (PRAGMO). River Restoration Centre, Cranfield, UK.

Harvey J.P. & Cowx I.G. (2002). A standardised survey and monitoring protocol for the assessment of lamprey populations within SAC rivers. Report to English Nature LIFE Rivers Project, 25 pp

Hendry, K., & Cragg-Hine, D. (2003). Ecology of the Atlantic Salmon. Conserving Natura 2000 Rivers Ecology Series No. 7. English Nature, Peterborough. https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=SMURF_salmon.pdf

Kemp, P. S., & O' Hanley, J. R. (2010). Procedures for evaluating and prioritizing the removal of fish passage barriers: a synthesis. *Fisheries Management and Ecology*, *17*(4), 297-322.

Li, W., & Milburn, L.-A. (2016). The evolution of geodesign as a design and planning tool. *Landscape and Urban Planning*, 156, 5-8.

Limburg, K. E., & Waldman, J. R. (2009). Dramatic declines in North Atlantic diadromous fishes. *BioScience*, *59*(11), 955-965.

Lucas, M.C., Bubb, D.H., Jang, M.-H., Ha, K., & Masters, J.E.G. (2009). Availability of and access to critical habitats in regulated rivers: Effects of low-head barriers on threatened lampreys. *Freshwater Biology*, 54(3), 621-634.

Maitland P.S. (2003). Ecology of river, brook and sea lamprey. Conserving Natura 2000 Rivers Ecology Series No. 4. English Nature, Peterborough.

McKay, S. K., Schramski, J. R., Conyngham, J. N., & Fischenich, J. C. (2013). Assessing upstream fish passage connectivity with network analysis. *Ecological applications*, *23*(6), 1396-1409.

McMillan-Wilhoit, J., Bastian, E., Hiett, M., Garfinkle, N., Foltz, T., Calfas, G. W., & Myers, N. (2018). A four-part framework for Geodesign software creation and research. *Transactions in GIS*, *22*(5), 1299-1309.

Moir, H.J., Gibbins, C.N., Soulsby, C., & Webb, J.H. (2006). Discharge and hydraulic interactions in contrasting channel morphologies and their influence on site utilization by spawning Atlantic salmon (Salmo salar). *Canadian Journal of Fisheries and Aquatic Sciences*, 63(11), 2567-2585.

Noble R.A.A., Goffaux D., Kestemont P. & Cowx I.G. (2007a). Harmonisation of the classification of the ecological characteristics of fish species for use in a standardised assessment method for the ecological integrity of European rivers. *Fisheries Management and Ecology* 14, 381-392.

Noble R.A.A., Cowx I. & Starkie A. (2007b). Development of fish-based methods for the assessment of ecological health in English and Welsh rivers. *Fisheries Management and Ecology* 14, 495-508.

Nunn, A. D., Copp, G. H., Vilizzi, L., & Carter, M. G. (2010). Seasonal and diel patterns in the migrations of fishes between a river and a floodplain tributary. *Ecology of Freshwater Fish*, *19*(1), 153-162.

Nunn, A. D, Harvey, J. P, & Cowx, I. G. (2007). The food and feeding relationships of larval and 0 year juvenile fishes in lowland rivers and connected waterbodies. I. Ontogenetic shifts and interspecific diet similarity. *Journal of Fish Biology*, 70(3), 726-742.

Nunn, A. D., Harvey, J. P., Noble, R. A. A., & Cowx, I. G. (2008). Condition assessment of lamprey populations in the Yorkshire Ouse catchment, north-east England, and the potential influence of physical migration barriers. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *18*(2), 175-189.

Nunn, A. D., & Cowx, I. G. (2012). Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys. *Ambio*, *41*(4), 402-409.

Nunn, A. D, Cowx, I. G. & Harvey, J. P. (2012). Hydropower Assessment Methodology: Engaging with Local Planners, the Environment Agency and Stakeholders to Develop Guidance, Data and Tools: Prioritizing passage improvements for diadromous fishes and lampreys in the Humber basin and River Trent. Report to Climate East Midlands and Environment Agency, Nottingham, 24 pp.

Palmer, M. A., Hondula, K. L., & Koch, B. J. (2014). Ecological restoration of streams and rivers: shifting strategies and shifting goals. *Annual Review of Ecology, Evolution, and Systematics*, *45*, 247-269.

Radinger, J., Essl, F., Hölker, F., Horký, P., Slavík, O., & Wolter, C. (2017). The future distribution of river fish: The complex interplay of climate and land use changes, species dispersal and movement barriers. *Global Change Biology*, 23(11), 4970-4986.

Radinger, J., Hölker, F., Horký, P., Slavík, O., & Wolter, C. (2018). Improved river continuity facilitates fishes' abilities to track future environmental changes. *Journal of Environmental Management*, 208, 169-179.

Radinger, J., & Wolter, C. (2015). Disentangling the effects of habitat suitability, dispersal, and fragmentation on the distribution of river fishes. *Ecological Applications*, 25, 914– 927.

Renaud, C. B. (1997). Conservation status of Northern Hemisphere lampreys (Petromyzontidae). *Journal of Applied Ichthyology*, 13(3), 143-148.

Reyjol Y., Hugueny B., Pont D., Bianco P.G., Beier U., Caiola N. Casals F. COWX I.G., Economou A, Ferreira T, Haidvogl G., Noble R., De Sostoa A., Vigneron T. & Virbickas T. (2007). Patterns in species richness and endemism of European freshwater fish. *Global Ecology and Biogeography* 16, 65–75

Roni, P., & Beechie, T. (2013). Introduction to restoration: key steps for designing effective programs and projects. *Stream and watershed restoration, a guide to restoring riverine processes and habitats. Wiley*, 1-11.

Roni, P., Hanson, K., & Beechie, T. (2008). Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management*, *28*(3), 856-890.

Skidmore, P, Pess, G, Castro, J, Shea, C, Cluer, B, Beechie, T, & Thorne, C. (2011). RiverRAT: Tools and Science for Assessing River Management and Restoration Projects. World *Environmental and Water Resources Congress* 2011, 2582-2592.

Steinitz, C. (2012). *A framework for Geodesign: changing geography by design*. (First ed.). ESRI Press.

van Zyll de Jong, M. & Cowx, I. G. (2016). Long-term response of salmonid populations to habitat restoration in a boreal forest stream. *Ecological engineering*, *91*, 148-157.

White, E. M., & Knights, B. (1997). Environmental factors affecting migration of the European eel in the Rivers Severn and Avon, England. *Journal of Fish Biology*, *50*(5), 1104-1116.

Table 1 Determination of “Fish stock status” for Atlantic salmon, European eel and river lamprey

	Density (# 100 m^{-2})			
Score	Salmon	Eel	Lamprey	Status
1	>5	>20	>10	Very good
2	3-5	11-20	6-10	Good
3	1-2	5-10	1-5	Moderate
4	<1	<5	<1	Poor
5	0	0	0	Very poor

Note that the class boundaries can be adjusted (standardised against the maximum value in the study) to suit species (e.g. rare vs. common) or study areas (e.g. low vs. high productivity), and that the metric refers to the ‘non-migratory’ life periods of the target species that inhabit rivers (e.g. larval and juvenile Atlantic salmon, juvenile European eel, larval river lamprey)

Table 2 Determination of “Likelihood of access”

		Distance from tidal limit (km)		
		<30	30-70	>70
Passage efficiency at downstream barriers	Low (<30%)	3	2	1
	Moderate (30-70%)	4	3	2
	High (>70%)	5	4	3

Note that the class boundaries can be adjusted (standardised against the maximum value in the study) to suit study areas (e.g. small vs. large catchments), and that the score of a given structure will necessarily be lower than those of any barriers downstream.

Table 3 Determination of “Habitat quantity”

	River length (km)	
Score	Humber	Trent
1	<5	<1
2	5-10	1-5
3	11-15	6-10
4	16-20	11-15
5	>20	>15

Note that the class boundaries can be adjusted (standardised against the maximum value in the study) to suit study areas (e.g. small vs. large catchments), and that tributaries can be included in the estimates if appropriate

Table 4 Determination of "Habitat quality"

		Water quality*		
		Good	Fair	Poor
Physical habitat	Poor (little or no suitable habitat present)	3	2	1
	Fair (sub-optimal habitat present)	4	3	2
	Good ('optimal' habitat present)	5	4	3

*_e.g. chemical General Quality Assessment (GQA) grades A-B (Good), C-D (Fair), E-F (Poor). Note that the metric refers to the habitat requirements of the life period of the target species that migrates into rivers (e.g. spawning habitat for adult Atlantic salmon and river lamprey, nursery habitat for juvenile European eel)_

Table 5 Representative data for all barriers were presented including B-value data for each case (Table 5- From Nunn and Cowx 2012).

Barrier	Species	F	P	A	Hqn	Hql	B	∑B	Rank
1	Salmon	4	4	5	2	3	480	2030	1
	Eel	4	5	5	2	4	800		
	Lamprey	5	5	5	2	3	750		
2	Salmon	4	3	3	3	3	324	1296	2
	Eel	4	3	3	3	4	432		
	Lamprey	5	4	3	3	3	540		
3	Salmon	4	4	3	2	3	288	1032	3
	Eel	4	4	3	2	4	384		
	Lamprey	5	4	3	2	3	360		
4	Salmon	4	4	2	2	3	192	688	4
	Eel	4	4	2	2	4	256		
	Lamprey	5	4	2	2	3	240		
5	Salmon	4	4	1	3	3	144	612	7
	Eel	4	3	2	3	4	288		
	Lamprey	5	3	2	2	3	180		
6	Salmon	4	3	2	2	3	144	640	5
	Eel	4	4	2	2	4	256		
	Lamprey	5	4	2	2	3	240		
7	Salmon	4	4	2	2	4	256	624	6
	Eel	4	2	2	2	4	128		
	Lamprey	5	3	2	2	4	240		

Note B is 'Barrier' Score, F is the 'Fish stock status', P is the 'Passage efficiency', A is the 'Likelihood of access', Hqn is the 'Habitat quantity' and Hql is the 'Habitat quality'

Table 6 Consequence table summarizing the impact of each alternative option on percentage increase in each habitat class and cumulative increases for each species where AS – Atlantic salmon; EE- European eel and, RL- river lamprey. Individual species and cumulative maximum are indicated in bold.

	1-4	1-7	1-2	1-3	1-5	1-6	2-3	2-4	2-5	2-6	2-7	3-4	3-5	3-6	3-7	4-5	4-6	4-7	5-6	5-7	6-7
Class 3 AS	94	45	72	77	89	70	59	77	72	52	27	82	77	57	32	94	75	50	70	45	25
Class 4 AS	0	388	0	0	0	0	0	0	0	0	388	0	0	0	388	0	0	388	0	388	388
Class 3 EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Class 4 EE	79	48	62	66	62	73	45	58	41	52	27	62	45	55	31	58	69	44	52	27	38
Class 3 RL	142	75	135	118	111	130	104	128	97	116	60	111	80	99	44	104	123	67	93	37	56
Class 4 RL	0	93	0	0	0	0	0	0	0	0	93	0	0	0	93	0	0	93	0	93	93
Cumulative AS	94	432	72	77	89	70	59	77	72	52	415	82	77	57	420	94	75	**437**	70	432	412
Cumulative EE	79	48	62	66	62	73	45	58	41	52	27	62	45	55	31	58	**69**	44	52	27	38
Cumulative RL	142	**168**	135	118	111	130	104	128	97	116	154	111	80	99	137	104	123	160	93	130	149
Cumulative Total	315	**648**	269	261	263	273	208	262	210	220	595	254	202	212	587	256	266	641	214	589	599

Note each column (e.g. '1-4', '1-7', etc.) represent the unique 2-barrier combination using those barriers. There are 21 possible combinations total for the 7 case study barriers. (i.e. (n!/r!(n-r)!) = 21 for n =7 and r = 2).

Design Team

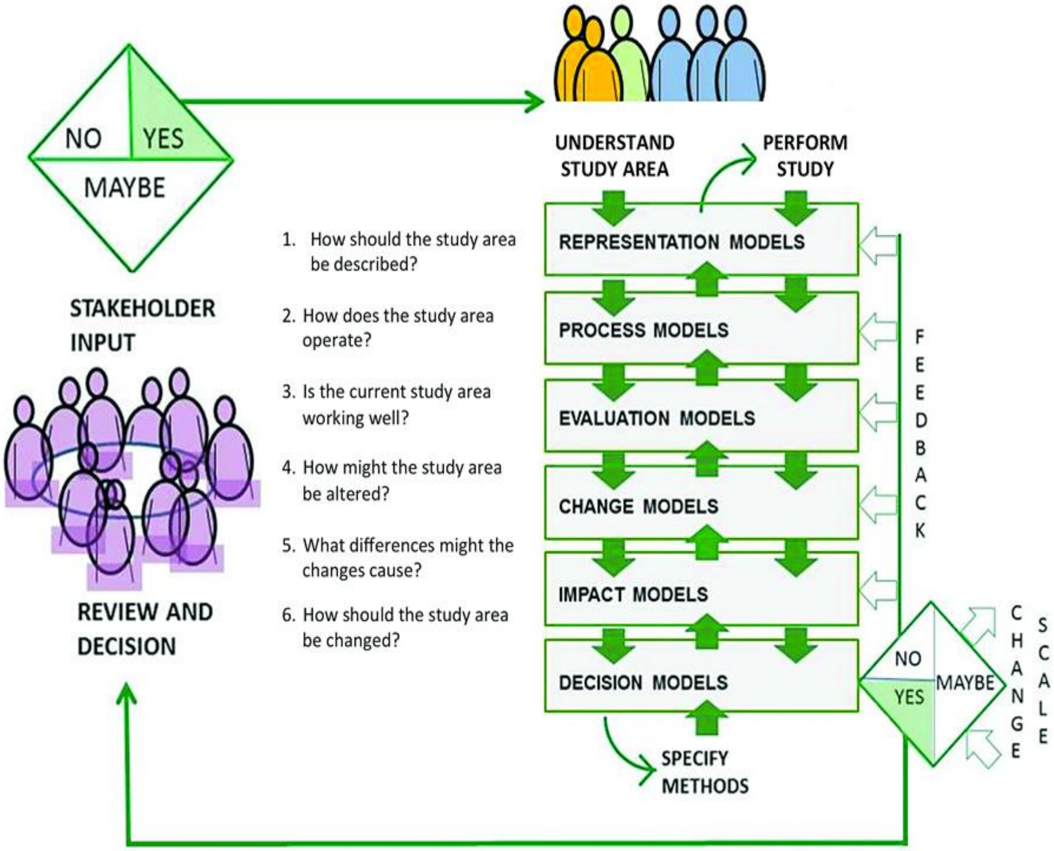


Fig 1. General Geodesign Framework (Adapted from Steinitz 2012)

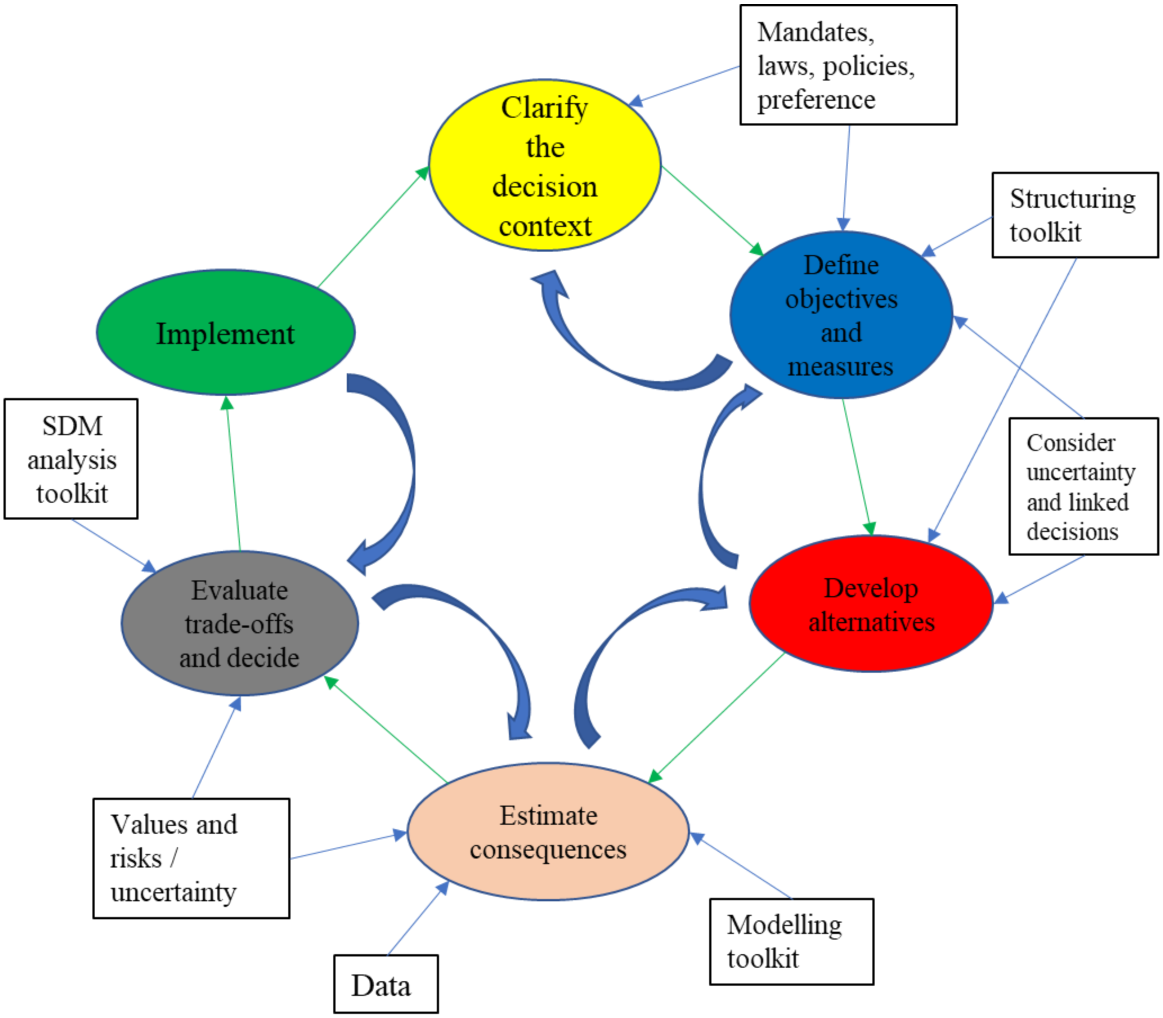


Fig 2 Structured Decision-Making (SDM) Process (adapted from Gregory et al. 2012)

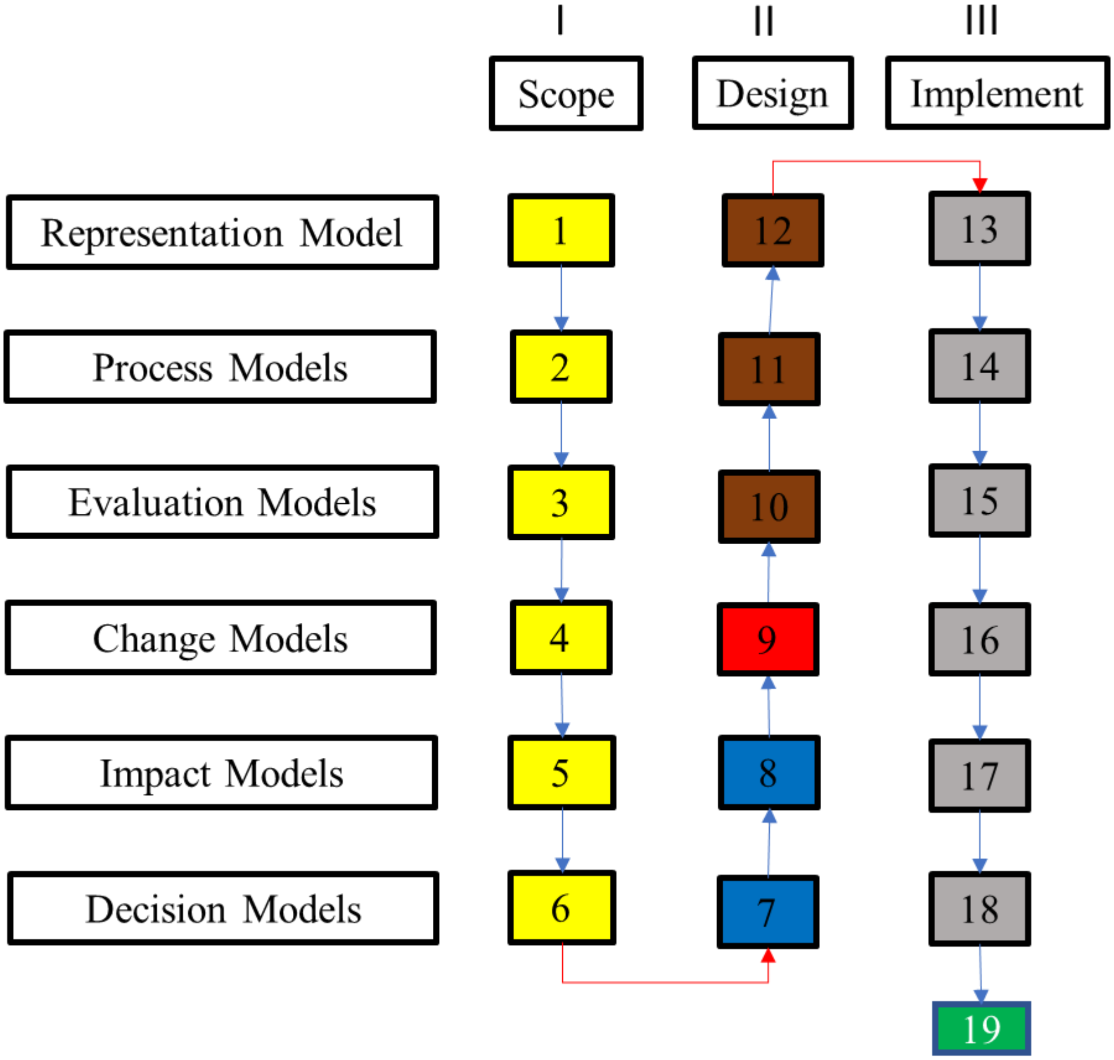
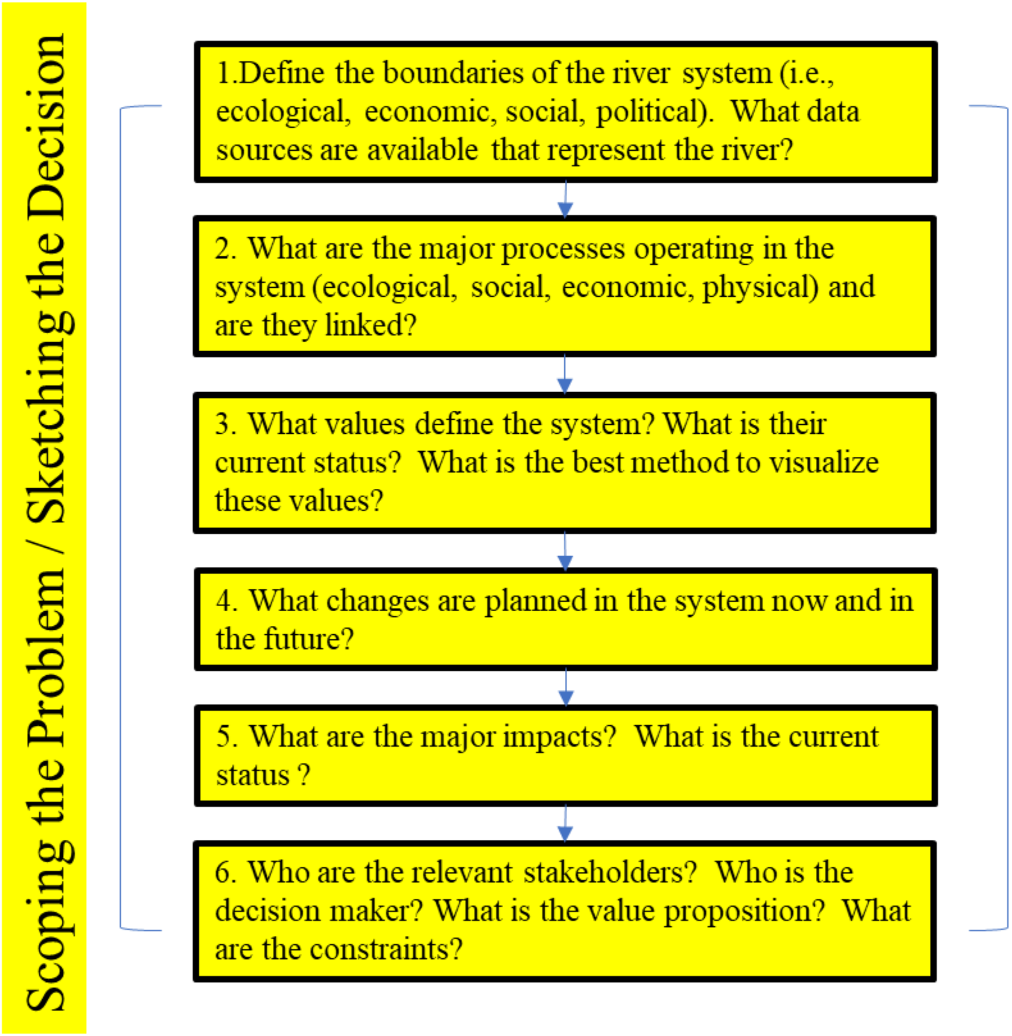


Fig 3. River Restoration Planning and Analysis Workflow (Adapted from Gregory 2012 and Steinitz 2012)



1.Define the boundaries of the river system (i.e., ecological, economic, social, political). What data sources are available that represent the river?

2. What are the major processes operating in the system (ecological, social, economic, physical) and are they linked?

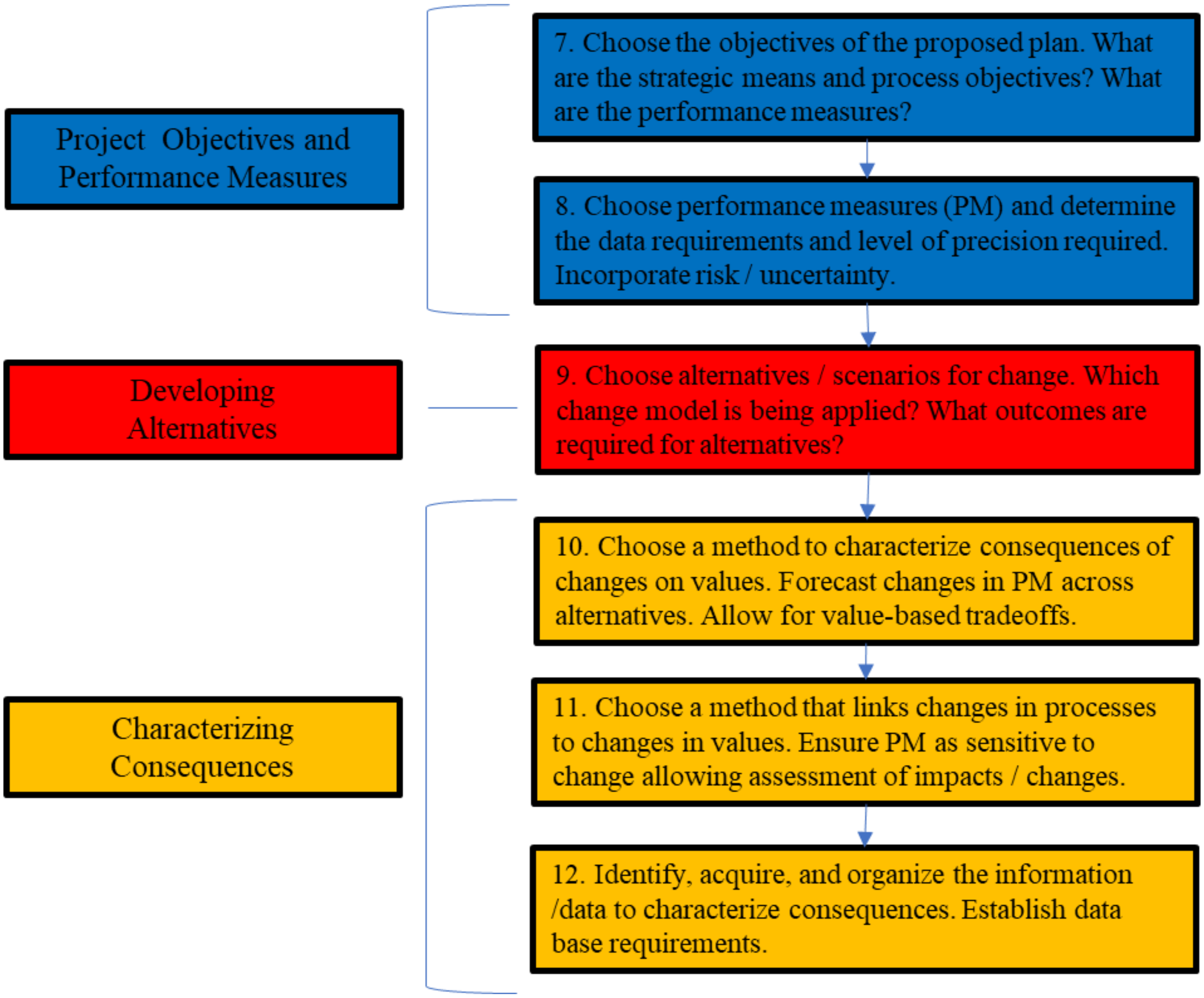
3. What values define the system? What is their current status? What is the best method to visualize these values?

4. What changes are planned in the system now and in the future?

5. What are the major impacts? What is the current status ?

6. Who are the relevant stakeholders? Who is the decision maker? What is the value proposition? What are the constraints?

Fig 4 Iteration 1 depicted as a spatial flow with associated questions and requirements



7. Choose the objectives of the proposed plan. What are the strategic means and process objectives? What are the performance measures?

8. Choose performance measures (PM) and determine the data requirements and level of precision required. Incorporate risk / uncertainty.

9. Choose alternatives / scenarios for change. Which change model is being applied? What outcomes are required for alternatives?

10. Choose a method to characterize consequences of changes on values. Forecast changes in PM across alternatives. Allow for value-based tradeoffs.

11. Choose a method that links changes in processes to changes in values. Ensure PM as sensitive to change allowing assessment of impacts / changes.

12. Identify, acquire, and organize the information /data to characterize consequences. Establish data base requirements.

Fig 5. Iteration 2 depicting the method of design, information flow with questions.

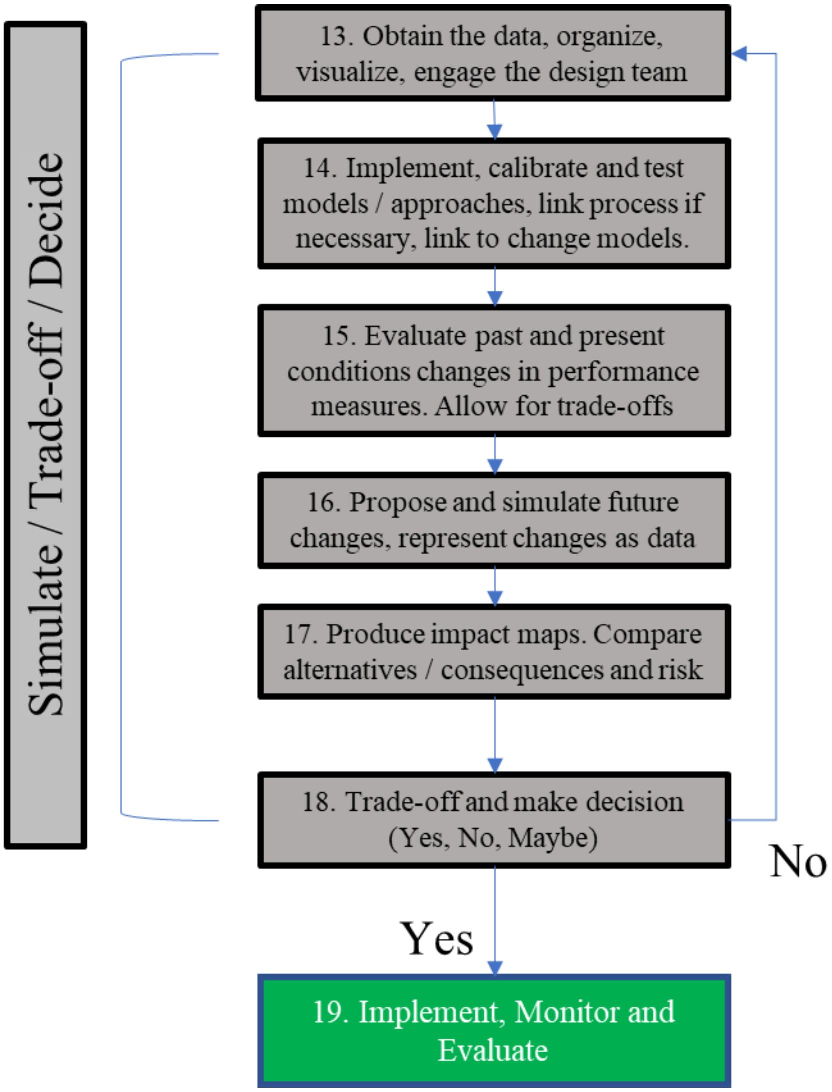


Fig 6 – Iteration 3 is a fully developed implementation

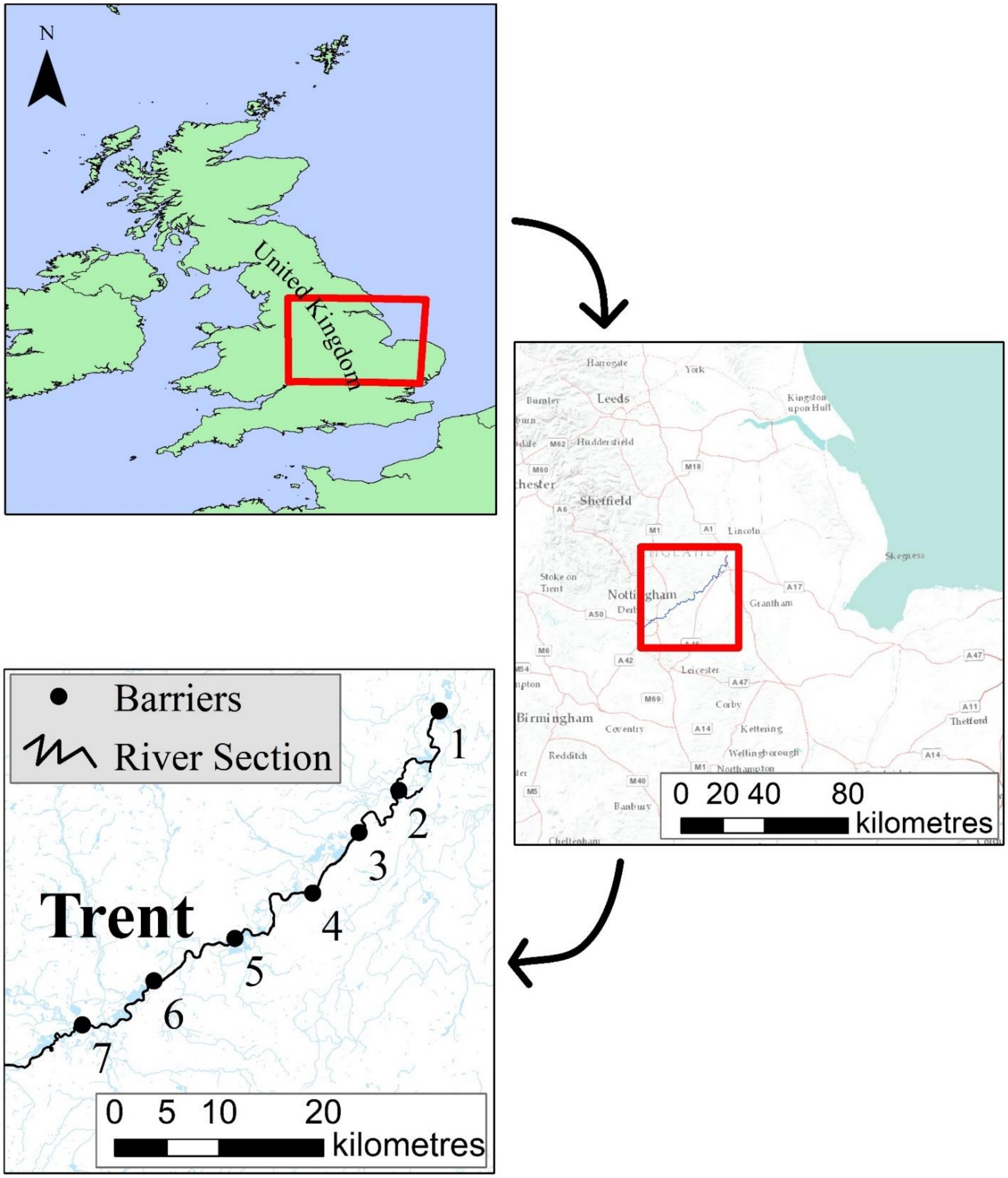


Fig 7 The River Trent, UK and the location of the case study barriers.

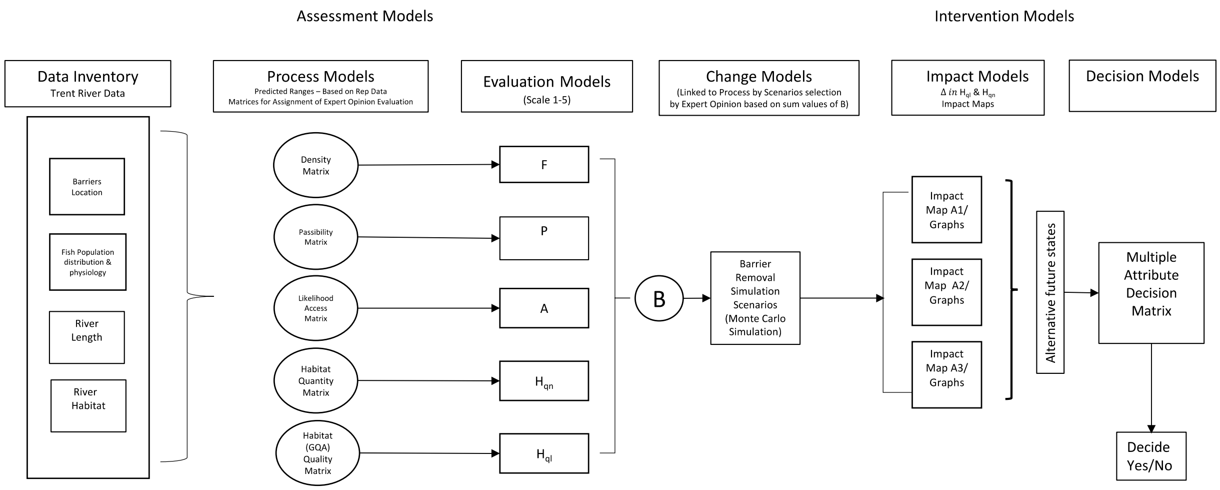


Fig 8. Fully populated and parameterized design work flow for implementation showing all data and sequential modelling steps for the case study (River Trent) decision

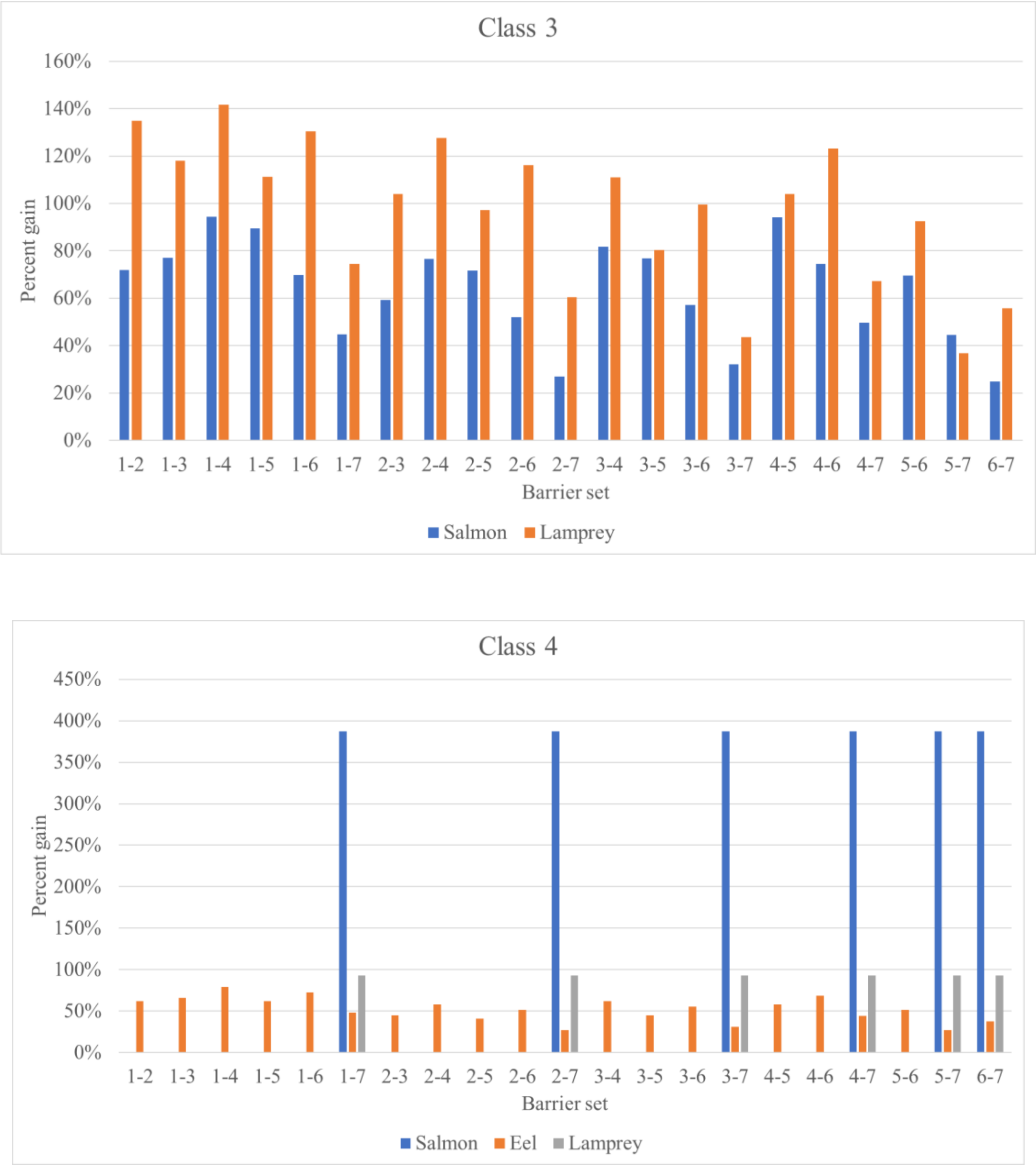


Fig 9 Cumulative percentage increase in (a) class 3 and (b) class 4 accessible habitat amounts for all three species for all 21 possible combinations of paired barrier restoration scenarios.

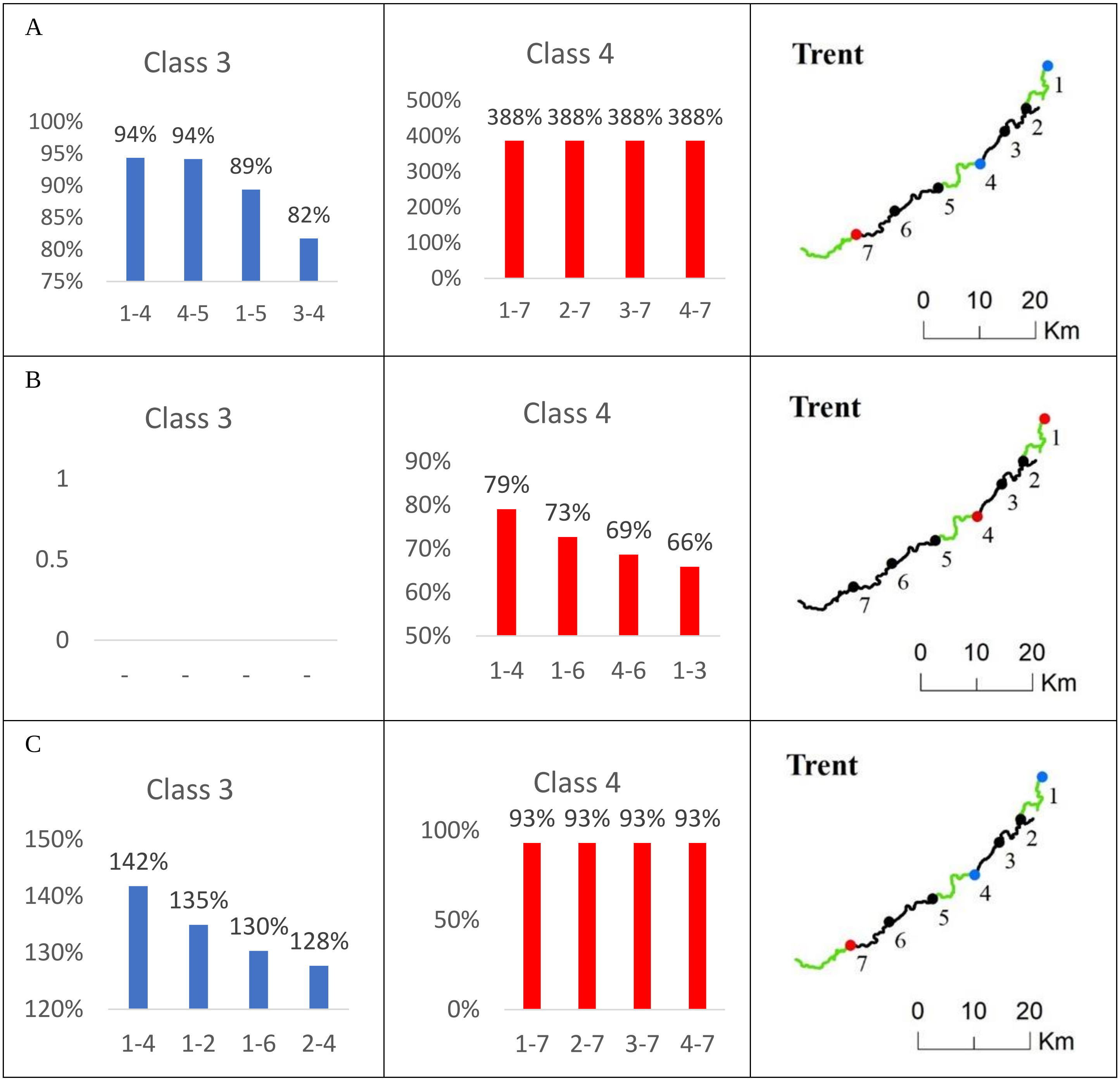


Fig 10 Example of live output from the multiple attribute decision making (MADM) matrix showing maximum increases in habitat class across all three-target species and a map depicting the spatial distribution of the habitat increases in the river section. Row A is Atlantic salmon, row B is European eel, and row C is River lamprey. For column 3, the blue dots on the maps are barrier combination with greatest class 3 increase, red dots additionally show greatest class 4 increase barrier(s). Map river sections shown in green are key habitat areas associated with greatest increase scenarios.