Thesis for the degree of a doctor of philosophy in Management Science

Economic Valuation and Optimisation of River Barrier Mitigation Actions

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April 2015

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Word Count : 37,960

Contents

Acknowledgments

I am extremely grateful to Jesse O'Hanley and Iain Fraser for their excellent supervision and support. I am also very grateful to Alex Abbott and Jed Wright of the US Fish and Wildlife for the provision of data used in the Maine case study, Duncan Hornby of the GoeData Institute, University of Southampton for processing the Maine data using the Barrier Analysis Tool (BAT) plug-in for ArcGIS, Lynda Newbold and Paul Kemp of the International Centre for Ecohydraulics Research, University of Southampton for the provision of data used in the River Wey case study and Matt Diebel of the U.S. Fish and Wildlife Service for processing the River Wey data. Special thanks go to the Economic and Social Research Council (ESRC) for supporting this PhD research via the South East Doctoral Training Centre (Grant No. ESJ500148/1) and to the faculty of social sciences at the University of Kent for funding administration of the CE surveys.

1. Introduction

River systems comprise one of the most complex, dynamic and bio-diverse ecosystems on earth and they also play an essential role in the transport of organisms and matter through the landscape. However, as a society we have extensively modified river systems across the globe in order to provide socioeconomic benefits such as water supply, flood suppression, power and transport infrastructure. Obtaining these benefits involves the construction of structures (barriers) that fragment the continuity of rivers. This restricts habitat accessibility and population interactions for a range of aquatic species. Numerous studies have demonstrated the negative effects of these artificial river barriers on both migratory and resident fish populations.

In light of the above, river barrier removal or mitigation (e.g., installation of fish passes) is viewed as one of the most cost effective means of improving fish populations at the watershed scale. There now exists a number of legislative drivers for implementing river barrier mitigation projects, notably the Water Framework Directive (WFD) and Eel recovery plan in the EU and the endangered species act in the US. Across England and Wales, the Environment Agency (EA) has prioritized 2,500 river barriers for mitigation action in order to meet such regulatory requirements. This prioritization exercise has been based on expert local knowledge of river catchments, where each barrier is considered separately, rather than as part of a network in which the effects of barrier mitigation actions are interactive. Consequently, the cost of removing and repairing these barriers (estimated at £540M) may represent poor value. More sophisticated prioritization techniques are needed, which ensure that resources are directed and spent efficiently.

Healthy fish populations are essential to the provision of many of the ecosystem services that rivers provide. As these services contribute to human well-being, the continued presence of barriers in many river systems may not be justified based on economic efficiency grounds. Accordingly, there is considerable interest amongst policy makers and river managers in estimating the economic benefits from investing in river barrier mitigation. In particular, this information is required to inform cost benefits analysis (CBA). This can assist in developing effective policy responses to the problem of river fragmentation at national, regional and catchment scales. In this regard, the WFD specifically requires CBA of river restoration projects when developing catchment management plans.

The overarching aim of this PhD project is to develop a framework for simultaneously generating optimal river barrier mitigation plans and estimating the economic benefit of improved ecosystem services delivery resulting from their implementation.

This type of analysis is of importance to river management as it can demonstrate when river barrier mitigation is economically rational and determine socially optimal levels of investment in this activity. This can, in turn, direct an efficient allocation of economic resources to the problems of environmental protection. It is believed that ensuring river barrier mitigation plans are optimal with respect to both cost and economic efficiency is crucial if the environmental goals of investing in this activity are not to be compromised in light of scarce economic resources. In order to achieve this objective, two avenues of research are pursued in this thesis.

In avenue one, a mixed integer linear program (MILP) is developed for maximizing habitat gains for migratory fish from river barrier mitigation action, subject to a budgetary constraint (Chapter 2). This model is demonstrated using case studies from the US states of Washington and Maine. An extension of the model is then developed for the more complex case of resident fish species (Chapter 3). An alternative formulation for resident fish that can be used in conjunction with statistical approaches is further presented to maximize estimated gains in fish species richness. These optimization models are applied to a case study, the River Wey, in South East England.

In avenue two, the value of ecosystem service improvements delivered via barrier mitigation is estimated using choice experiments (Chapter 4). This allows the marginal willingness-to-pay (implicit price) for fish species richness and abundance responses to river barrier mitigation to be estimated. The choice experiment was administered nationally and to a sample of residents living locally to the River Wey .

The two avenues of research are combined to illustrate how the methods developed in this thesis can be used to undertake a cost benefit analysis (CBA) of investments in river barrier mitigation action (Chapter 5). Specifically, it is shown how the benefit value of net fish species gains can be maximized via a MILP using the implicit price generated from the choice experiments. A demonstration of this CBA approach using the River Wey and its catchment population is provided.

CBA of environmental policies, such as river barrier mitigation, is now routinely carried out by environmental agencies, for instance under government rule-making in the US and the WFD in the EU. Consequently, it is believed that the framework developed in this thesis can be of direct benefit to both policy makers and practitioners involved in river ecosystem management and barrier mitigation. The conceptual framework for the PhD project and key components of the four main research chapters is presented in the Figure 1.1. The introductory sections for each chapter provide a detailed account of the context in which each distinct research element was undertaken. Whilst the chapters build towards the overarching goal of the thesis, they are also intended to exist as standalone research articles.

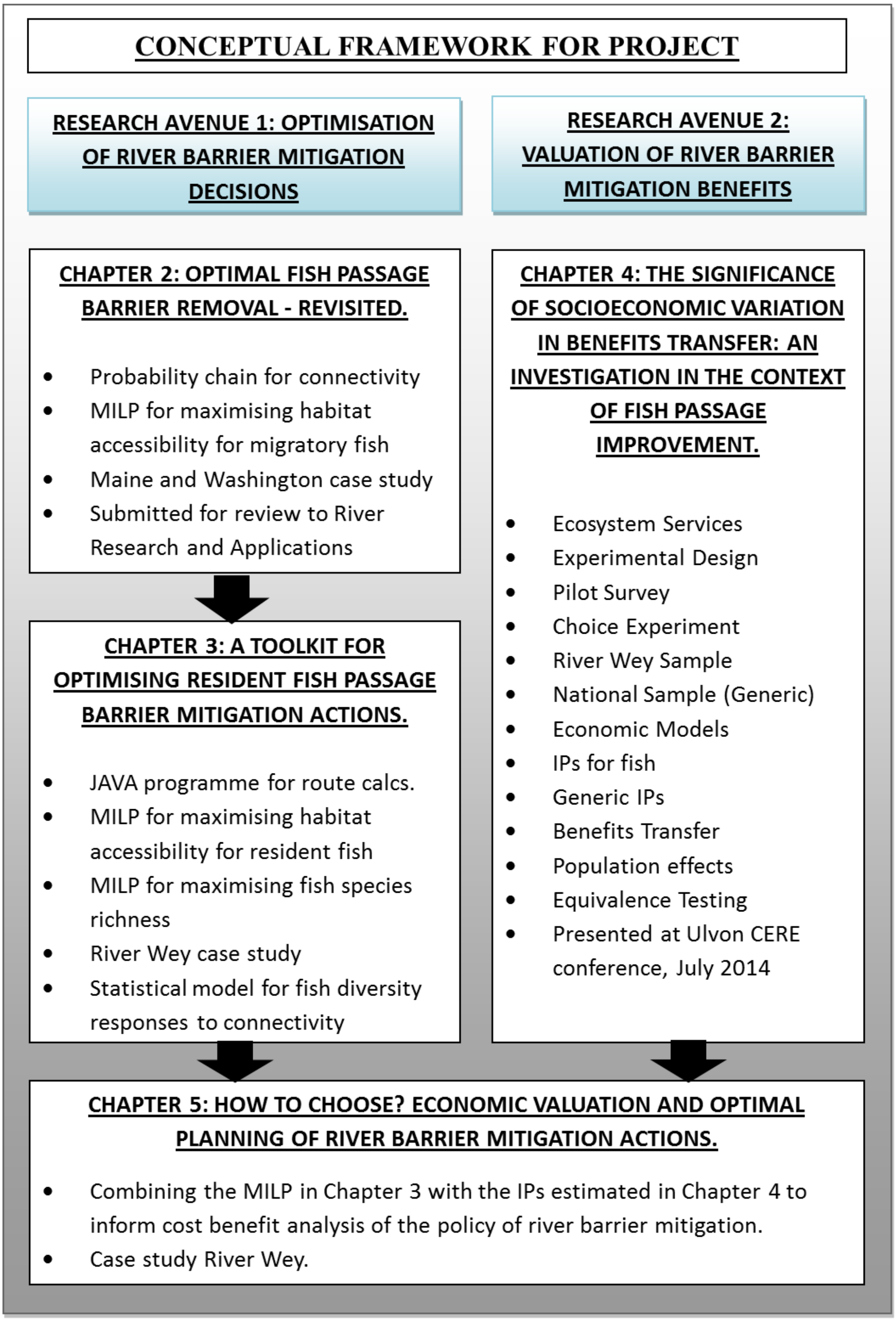


Figure 1.1.: Conceptual Framework for PhD Thesis.

2. Optimal Fish Passage Barrier Removal - Revisited

2.1. Abstract

Infrastructure, such as dams, weirs and culverts, disrupt the longitudinal connectivity of rivers, causing adverse impacts on fish and other aquatic species. Improving fish passage at artificial barriers, accordingly, can be an especially effective and economical river restoration option. This chapter presents a novel, mixed integer programing model for optimizing barrier mitigation decisions given a limited budget. Rather than simply treating barriers as being impassable or not, the more general case in which barriers may be partially passable is considered. Although this assumption normally introduces non-linearity into the problem, a linear model is formulated via the use of *probability chains*, a newly proposed technique from the operations research literature. The model is noteworthy in that it can be readily implemented and solved using off-the-shelf optimization modeling software. The model is tested using two case-studies, which demonstrate it to be highly efficient in comparison to existing solution methods and, moreover, highly scalable in that large problems approaching 7,000 barriers can still be solved optimally. Analysis confirms that barrier mitigation can provide substantial ecological gains for migratory fish species at low levels of investment.

2.2. Introduction

River systems comprise some of the most complex, dynamic and bio-diverse ecosystems on earth, as well as playing an essential role in the transport of organisms and matter through the landscape (Dynesius and Nilsson, 1994). At the same time, river systems across the globe have been modified extensively in order to provide socioeconomic benefits like water supply, flood suppression, power generation and transportation infrastructure (Heinz Center, 2002). A global review of large river systems identified more than 50% as being affected by river barriers such as dams, culverts and weirs (Nilsson et al., 2005). In the United States, only 2% of streams are believed to be free flowing and relatively undeveloped (Pringle, 2003). River barriers fragment the continuity of rivers and substantially alter their natural flow, thereby transforming the biological, morphological and physio-chemical characteristics of rivers and associated ecosystems (Bednarek, 2001). The presence of physical obstructions to migratory fish (e.g., salmon and eel) can reduce or eliminate their ability to reach high quality spawning and rearing grounds (Stanford et al., 1996).

While large head dams do impose major obstacles, the cumulative effect of low head dams, road crossings and other smaller barriers can be even greater due to their large number (Roni et al., 2002; de Leaniz, 2008). Numerous studies have demonstrated the negative effects small artificial barriers have on migratory and resident fish populations (Sheer and Steel, 2006; Catalano et al., 2007; Fullerton et al., 2010; Nislow et al., 2011). Culverts, for example, can hinder fish passage due to high water velocities, inadequate depths, debris jams or large outflow drops (Roni et al., 2002; Kemp and Williams, 2008). This can result in fish expending significant additional energy when migrating upriver as well as increased predation, angling mortality and disease in pooling areas below barriers. Individuals that are unsuccessful in passing barriers may be forced to spawn or rear in less suitable habitat downstream (e.g., in areas at increased risk of siltation or predation of eggs and larvae), thus further depressing population numbers (de Leaniz, 2008).

Removing migratory fish passage barriers has been demonstrated to result in increased spawning (Burdick and Hightower, 2006), fish density (Gardner et al., 2013), diversity (Catalano et al., 2007) and rapid colonization of formerly impounded upstream reaches (Roni et al., 2008). Moreover, there is good evidence that river barrier mitigation is one of the most cost-effective means of improving fish populations at the watershed scale (Roni et al., 2002). There are often important legislative drivers for improving river connectivity, such as the Endangered Species Act in the US and the Water Framework Directive in the EU.

Traditionally, studies on river barrier mitigation have concentrated on the assessment of localized connectivity improvements. Scoring and ranking procedures are a typical example and are commonly employed to prioritize barriers for mitigation action (e.g., Kocovsky et al., 2009 and Nunn and Cowx, 2012). However, scoring and ranking approaches consider each barrier independently and fail to account for the cumulative effects on longitudinal connectivity from improving passage at downstream barriers. Their use typically results in sub-optimal subsets of barriers being targeted for action (Kemp and O'Hanley, 2010). Understanding how passage improvement at multiple river barriers interact to affect fluvial connectivity is key to the sustainable management of rivers and the conservation of migratory fish species (Fullerton et al., 2010).

In broad terms, two general approaches can be identified in the literature that consider interactive effects of barrier mitigation, namely graph theoretic (e.g., Erős et al., 2011; Segurado et al., 2013) and optimization modeling frameworks (e.g., O'Hanley and Tomberlin, 2005; Kuby et al., 2005). Both of these methodologies model watersheds as Dendritic Ecological Networks (DENs), where the river network is characterized by a branching architecture with branches forming as one moves in the upstream direction (Grant et al., 2007).

2.2.1. Graph Theoretic Modeling

Graph theoretic approaches typically model river DENs as a set of river segments or habitat patches (nodes) and river confluences (arcs) (Padgham and Webb, 2010; Erős et al., 2011; Segurado et al., 2013). Barriers within the network can either be total (i.e., passability 0), thus splitting the graph into separate sub networks (Erős et al., 2011; Segurado et al., 2013) or partial (i.e., passability between 0 and 1), in which case transition between nodes is modeled via a transition probability matrix (Padgham and Webb, 2010). The positional importance of any habitat node can be evaluated using metrics like the Betweeness Centrality Index (BCI), which measures the number of shortest paths going through it (Pascual-Hortal and Saura, 2006). Overall habitat availability within a watershed can be captured by different metrics like the Integral Index of Connectivity (IIC), which takes into account both connectivity between habitat patches and habitat amount (Pascual-Hortal and Saura, 2006). The importance of any given barrier, in turn, can be identified by calculating the effect that restoring connectivity between nodes has on IIC (Erős et al., 2011; Segurado et al., 2013).

Whilst less common in the literature, an alternative approach in which DENs are constructed using barriers (nodes) and adjacencies between barriers (arcs) has proven insightful for assessing river connectivity (Cote et al., 2009; Diebel et al., 2014; McKay et al., 2013). Figure 2.1, presents an example of this approach with natural and artificial barriers represented as lettered nodes (A-F). In 2.1(a), basic information pertaining to each barrier is listed next to each node, including current passability (p^0), the cost (c) in thousands of dollars to fully repair/remove the barrier (i.e., increase passability to 1), and the amount of river habitat (h) immediate above the barrier. Barrier D is a natural barrier with no mitigation option available (i.e., c = NA). Assuming individual barrier passabilities are independent, connectivity from any given point in the network to habitat immediately above a barrier is simply taken as the product of the passabilities for all intervening barriers. This is more generally referred to as cumulative passability for barriers in series (Kemp and O'Hanley, 2010). To quantify habitat availability at the watershed level, various metrics have been proposed. Cote et al. (2009) describe the Dendritic Connectivity Index (DCI), which is calculated as the sum of the relative amount of net habitat above a barrier adjusted by the cumulative passability of the barrier. McKay et al. (2013) examine a conceptually similar index (the HCIU index) specifically for the case of upstream migrating fish. Diebel et al. (2014) present a more general connectivity metric (the C metric) specific to resident fish, which further accounts for multiple habitat types and the travel distance between habitat areas.

Examining the effect of barrier mitigation on river connectivity using indices such as IIC, DCI, HCIU and C can allow decision makers to choose the best course of action among an identified set of alternatives. Graph based approaches for prioritizing barrier mitigation action are certainly more insightful than traditional scoring and ranking approaches in that they consider basin-wide barrier impacts on river connectivity and the effect of coordinated mitigation action. However, they are “descriptive”, rather than “prescriptive”, in that they do not themselves produce a recommended solution. The final subset of barriers targeted for mitigation has no guarantee of being optimal unless all possible permutations of barrier mitigation action have been evaluated. While this is possible for situations involving a relatively small number of barriers, for watersheds with large numbers of barriers, considering every possible combination becomes computationally intractable.

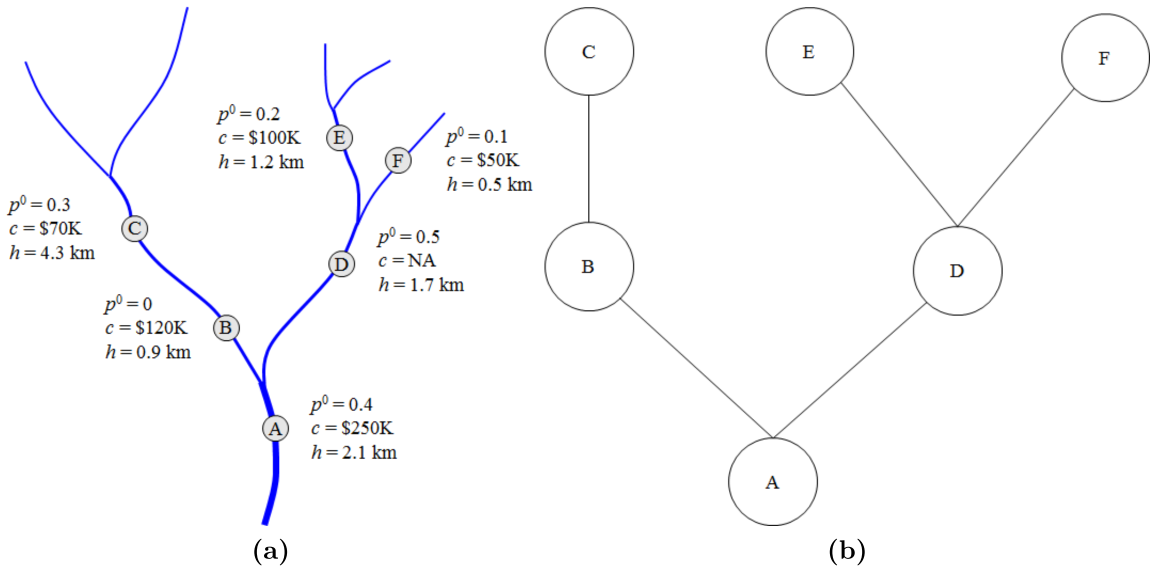


Figure 2.1.: Example of a river barrier network represented as a simple map (a) and as an equivalent DEN (b).

2.2.2. Optimization Modeling and Connectivity

Optimization models also normally employ graph structures to model DENs in the format presented in Figure 2.1 (i.e., barriers represented as nodes with arcs of habitat between adjacent barriers). Unlike simple graph theory models, optimization approaches provide a *scalable* method of exploring all possible combinations of barrier mitigation action so that an optimal solution can be identified which maximizes restoration gains given available resources. In addition, models can be formulated to address a variety of different objectives and / or include various planning constraints. For example, O’Hanley (2011) present a model particularly suited to resident fish species that maximizes the size of the largest barrier free sub-network within a river system, subject to a budget. Kuby et al. (2005) present a bi-objective model for removing hydropower dams that maximizes accessible habitat gains, while simultaneously minimizing economic losses associated with reduced power generation and water storage capacity. Zheng et al. (2009) optimize no less than 9 ecological and socio-economic objectives through the use of multicriteria value analysis, including fish biomass changes, ecosystem structure, function and productivity responses, and both dam removal and invasive species control costs. The approach is noteworthy for the combined use of optimization, multicriteria analysis, simulation and habitat suitability modeling. Zheng and Hobbs (2013) consider a similar type of multi-objective framework, focusing in particular on dam safety issues.

Structurally O'Hanley (2011), Kuby et al. (2005), Zheng et al. (2009) and Zheng and Hobbs (2013) formulate their optimization models as mixed integer linear programs (MILPs), in which the primary decision variables are binary to indicate whether any particular barrier should be repaired/removed or not. In order to maintain linearity of the models, these studies all assume that passability is also binary (i.e., barriers are either completely impassable or passable, 0 and 1, respectively), thus directly equating to decisions about barrier repair/removal. In contrast, O'Hanley and Tomberlin (2005) adopt the more general view, as done in Cote et al. (2009), Diebel et al. (2014) and McKay et al. (2013), that barriers may be partially passable (i.e., anywhere in the range 0 to 1). In the context of diadromous fish, access to river habitat above a barrier is taken (assuming barriers are independent) as the product of all downstream barrier passability values. Unfortunately, multiplying barrier passabilities introduces nonlinear interactions among the decision variables. This normally makes such optimization models hard to solve. O'Hanley and Tomberlin (2005) resort to the use of dynamic programming (DP) and heuristic methods.

This chapter presents an efficient *linear* model for optimizing river barrier repair and removal decisions in order to maximize upstream habitat gains for migratory fish. Specifically, the Fish Passage Barrier Removal Problem (FPBRP) model proposed by O'Hanley and Tomberlin (2005) is reformulated as a MILP based on the newly proposed technique of forming probability chains to evaluate cumulative passability terms (O'Hanley et al., 2013a). The benefits of a linear model are twofold. First, it allows FPBRP to be coded using high-level algebraic modeling languages such as OPL, AMPL or GAMS and subsequently be solved using off-the-shelf optimization software solvers like CPLEX and GUROBI. Second, the increased efficiency and scalability of the model, in comparison to DP, allows far larger problems to be solved optimally.

The remainder of the chapter is organized as follows. The original nonlinear version of FPBRP as well as the new linear reformulation are presented in Section 2.3. Section 2.4 provides some simple examples to demonstrate how the linear model works. In Section 2.5, the linear model is compared to existing solution methods and the insight the FPBRP can provide is demonstrated using case study watersheds from the US. Concluding remarks are provided in Section 2.6. In Appendix A, an OPL implementation of the model and an example dataset that can be readily adapted into other modeling languages are provided.

2.3. The Fish Passage Barrier Removal Problem (FPBRP)

The FPBRP selects barriers for repair or removal in order to maximize the amount of accessible habitat for diadromous fish. It is assumed that barrier passabilities can take on fractional values in the range 0 to 1. Passability represents the probability that fish are able to pass a particular barrier. Given that fish naturally vary in their ability to negotiate barriers, the model allows for multiple barrier passability values to be specified for each “restoration target” of interest (e.g., species, guild or ecologically significant unit). Cumulative passability to habitat above any given barrier (aka accessibility) is taken as the product of the passability at that barrier and all barriers downstream to the river mouth. Cumulative passability is equivalent to longitudinal connectivity with the river mouth. The model assumes that multiple mitigation options (e.g., removal, replacement, fitting baffles, installing fish passes) may be available at any given barrier with varying cost and passability improvement but that only one project can be carried out at a barrier. Lastly, there is assumed to be a budget, which limits total expenditure on river barrier mitigation actions.

Table 2.1.: Notation used in FPBRP.

Symbol	Definition
T	Set of restoration targets, indexed by t
J	Set of artificial and natural barriers, indexed by j and k respectively
A_j	Set of mitigation projects available at barrier j, indexed by i
J^*	Set of barriers for which at least one mitigation project exists (i.e., $\|A_j\| \geq 1$), indexed by j
D_j	Set of all barriers downstream from and including barrier j
w_t	Objective weight for restoration target t
v_{jt}	Net amount of habitat above barrier j for restoration target t
c_{ij}	Cost of implementing mitigation project i at barrier j
b	Available budget for carrying out mitigation actions
p^0_{jt}	Initial passability of barrier j for restoration target t
p_{jit}	Increase in passability for restoration target t at barrier j given implementation of mitigation project i

2.3.1. Initial Formulation

In order to formulate the FPBRP, the notation provided in Table 2.1 and the following decision variables are employed.

$$x_{ji} = \begin{cases} 1 & \text{if mitigation project } i \text{is carried out at artifical barrier } j \\ 0 & \text{otherwise} \end{cases}$$

$z_{jt} =$ cumulative passability to habitat immediately above barrier $j$for restoration target t

A nonlinear formulation for FPBRP is then given as follows:

$$\text{FPBRP} \ \max \sum_{t \in T} w_t \sum_{j \in J} v_{jt} z_{jt} \tag{2.1}$$

s.t.

$$z_{jt} = \prod_{k \in D_j} \left(p^0_{kt} + \sum_{i \in A_k} p_{kit} x_{ki} \right) \qquad \forall j \in J, t \in T \tag{2.2}$$

$$\sum_{i \in A_j} x_{ji} \leq 1 \qquad \forall j \in J^* \tag{2.3}$$

$$\sum_{j \in J^*} \sum_{i \in A_j} c_{ji} x_{ji} \leq b \tag{2.4}$$

$$x_{ji} \in \{0, 1\} \qquad \forall j \in J^*, i \in A_j \tag{2.5}$$

The objective (2.1) calculates the weighted sum across all restoration targets t of the cumulative passability weighted habitat $v_{jt} z_{jt}$ above each barrier j. Target-specific weights w_t allow certain targets to be prioritized over others. Parameter v_{jt}, the net amount of habitat above barrier j for target t, can be measured as river length or area and can even be quality adjusted (discussed below). Cumulative passability $0 \leq z_{jt} \leq 1$ above barrier j for target t is calculated via the first set of constraints (2.2). They specify for a given barrier j and target t that z_{jt} is equal to the product of the passabilities in set D_j, namely barrier j and all barriers downstream from j to the river mouth. If no project is selected at a given barrier $k \in D_j$, then passability at k for restoration target t is p^0_{kt}. If project i is selected, then passability at k for restoration target t becomes $p^0_{kt} + p_{kit}$. Note that equations (2.2) are nonlinear. Constraints (2.3) ensure only one mitigation project i can be carried out at any given barrier. Inequality (2.4) stipulates that the total cost of barrier mitigation actions cannot exceed the total available budget b. Constraints (2.5) impose binary restrictions on the x_{ji} decision variables.

The FPBRP can prioritize particular habitat areas or types by assigning a habitat quality value q_{jt} (in the 0 to 1 range) to each subnetwork j for each restoration target t. The analyst may derive these quality values on a subnetwork by subnetwork basis or employ broader classification approaches, such as Strahler stream order or substrate conditions, to sets of subnetworks. q_{jt} provides a weighting factor to be applied directly to v_{jt} in the objective (2.1). The model may also be adapted to account for downstream passage by simply redefining parameter p^0_{jt} (p_{jit}) as the product of upstream passability $\overrightarrow{p}^{0}_{jt}$ ($\overrightarrow{p}_{jit}$) and downstream passability $\overleftarrow{p}^{0}_{jt}$ ($\overleftarrow{p}_{jit}$) for any given barrier j and target t. In this way, p^0_{jt} and p_{jit} would then represent *bi-directional* passability terms, thus allowing one to handle (using the salmon as an illustrative example) both the upstream passage of spawning adults and the downstream passage of juvenile smolts.

2.3.2. Linear Reformulation

The above nonlinear problem is hard to solve, even for modern optimization software and the general algebraic modeling system (GAMS). One way to overcome this difficulty is to reformulate FPBRP as a mixed integer linear program (MILP). In order to achieve this the following additional variable is introduced:

$y_{jit} =$ change in cumulative passability at barrier j given implementation of project $i$for target t

Further, let d_j refer to the barrier immediately downstream of j. The linear version of the FPBRP model is as above but with (2.2) replaced by the following:

$$z_{jt} = p^0_{jt} + \sum_{i \in A_j} y_{jit} \qquad \forall j \in J, d_j = \emptyset, t \in T \tag{2.6}$$

$$z_{jt} = p^0_{jt} z_{d_j t} + \sum_{i \in A_j} y_{jit} \qquad \forall j \in J, d_j \neq \emptyset, t \in T \tag{2.7}$$

$$y_{jit} \leq p_{jit} x_{ji} \qquad \forall j \in J^*, i \in A_j, t \in T \tag{2.8}$$

$$y_{jit} \leq p_{jit} z_{d_j t} \qquad \forall j \in J^*, d_j \neq \emptyset, i \in A_j, t \in T \tag{2.9}$$

Nonlinearity is removed from the model through the use of flow-balance constraints (2.6) and (2.7) for the determination of z_{jt} combined with bounding constraints (2.8) and (2.9) on y_{jit}. Collectively, the z_{jt} and y_{jit} variables and constraints (2.6)-(2.9) form a probability chain that iteratively propagates cumulative passability values from each barrier j to its next upstream barrier (O'Hanley et al., 2013a). Specifically, equations (2.6) specify for restoration target t that cumulative passability z_{jt} at a barrier j for which there is no downstream barrier ($d_j = \emptyset$) is equal to the initial passability p^0_{jt} plus the potential increase in passability y_{jit} for target t resulting from the implementation of any project i at j. Equations (2.7), meanwhile, specify for target t that the cumulative passability z_{jt} at any barrier j located above another barrier ($d_j \neq \emptyset$) is the product of p^0_{jt} and the cumulative passability at downstream barrier d_j ($z_{d_j t}$) plus the potential increase in cumulative passability y_{jit} of any project i at j. Inequalities (2.8) specify that if project i is not selected ($x_{ji} = 0$), then y_{jit} must equal 0. If project i is selected, then y_{jit} is bounded above by

p_{jit}, the maximum potential increase in cumulative passability at barrier j. For barriers without a downstream barrier, the value p_{jit} provides the exact increase in cumulative passability. Finally, inequalities (2.9) limit the increase in cumulative passability y_{jit} to be p_{jit} times cumulative passability at downstream barrier d_j (z_{d_jt}). Inequalities (2.9) become binding at upstream barriers j ($d_j \neq \emptyset$) when $x_{ji} = 1$. The new formulation has $\sum_{j \in J^*} \mid A_j \mid$ extra number of continuous variables but its resolution is relatively easier.

Figure 2.2 provides an illustrative example of a generic probability chain represented in graph form for a hypothetical barrier j whose initial passability p^0_{jt} for target species t can be improved via implementation of mitigation projects $i = 1, 2, \ldots n \in A_j$, thereby resulting in an increase in cumulative passability z_{jt} to areas upstream of j.

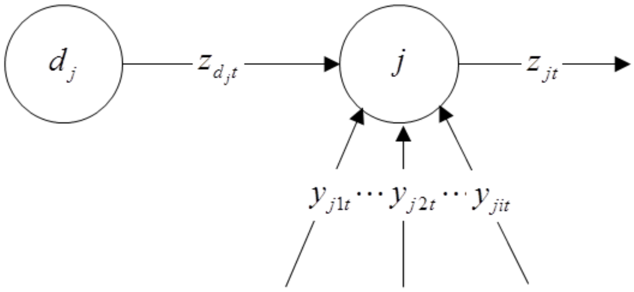


Figure 2.2.: Probability chain for a hypothetical barrier j.

2.3.3. Negative Weight Targets

The FPBRP model considers the case where habitat access for all target species is considered a positive ecological outcome. However, there may be target species for which it is desirable to limit habitat gain (e.g., invasive species) by assigning a negative objective weight (w_t). In order to accommodate undesirable targets, the following additional constraints applicable to the negative weighted targets only must be added:

$$y_{jit} \geq p_{jit} x_{ji} \qquad \forall j \in J^*, d_j = \emptyset, i \in A_j, t \in T \tag{2.10}$$

$$y_{jit} \geq p_{jit} z_{d_jt} + x_{ji} - 1 \qquad \forall j \in J^*, d_j \neq \emptyset, i \in A_j, t \in T \tag{2.11}$$

$$y_{jit} \geq 0 \qquad \forall j \in J^*, d_j \neq \emptyset, i \in A_j, t \in T \tag{2.12}$$

Inequalities (2.10) to (2.12) allow negatively weighted targets by forcing the improvements in cumulative passability for these species to reduce the objective value determined in (2.1), which would not occur via inequalities (2.8) and (2.9). Specifically, inequalities (2.10) ensures that if project i is implemented at barrier j for which there are no downstream barriers ($d_j = \emptyset$), then the associated increase in cumulative passability beyond this barrier is applied to the negatively weighted targets (i.e., y_{jit} is bounded from below). Inequalities (2.11) are similarly binding with respect to cumulative passability beyond all upstream barriers j ($d_j \neq \emptyset$) when mitigation is carried out (i.e., $x_{ji} = 1$). Finally, inequalities (2.12) ensure cumulative passability beyond upstream barriers remains non-negative when mitigation is not carried out (i.e., when $x_{ji} = 0$ and the right hand side of inequality (2.11) is negative).

2.4. Simple Example Problem

In order to illustrate how cumulative passability terms z_{jt} are evaluated along a probability chain, consider a simple example of three artificial river barriers 1-3 located in series above the river mouth, as shown in Figure 2.3. For simplicity, it is assumed that there is a single restoration target, which allows index t to be dropped from the notation. Initial passabilities for barriers 1-3 are given as $p_1^0 = 0.5$, $p_2^0 = 0.7$ and $p_3^0 = 0.2$, respectively. It is also assumed that only a single mitigation project is available at any given barrier, allowing i to also be dropped from the notation, and that this restores a barrier to full passability (i.e., $p_1 = 0.5$, $p_2 = 0.3$ and $p_3 = 0.8$).

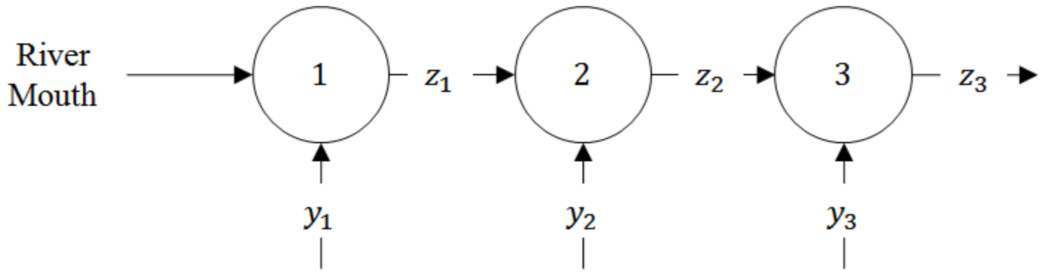


Figure 2.3.: Single stream channel with three artificial barriers located in series above the river mouth.

2.4.1. Case 1: No Mitigation

If no mitigation projects are carried out at any of the barriers (i.e., $x_1 = x_2 = x_3 = 0$), then cumulative passability of the third barrier, according to equation (2.2), is simply the product of the initial passabilities of the three barriers (i.e., $z_3 = 0.5 \times 0.7 \times 0.2 = 0.07$). Alternatively, using the linear model z_3 can be determined iteratively using the probability chain (2.6)-(2.9). Since no mitigation is carried out, based on (2.8), it follows that $y_1 = y_2 = y_3 = 0$. According to (2.6), for barrier 1:

$$z_1 \; = \; p_1^0 + y_1 \; = \; 0.5 + 0 \; = \; 0.5$$

while based on (2.7), for barriers 2 and 3:

$$z_2 \;=\; p_2^0 z_1 + y_2 \;=\; 0.7 \times 0.5 + 0 \;=\; 0.35$$

$$z_3 \;=\; p_3^0 z_2 + y_3 \;=\; 0.2 \times 0.35 + 0 \;=\; 0.07$$

As demonstrated above, the linear model produces a cumulative passability value for the third barrier that is equivalent to the nonlinear model. Simple inspection shows that the same also holds for the first and second barriers as well.

2.4.2. Case 2: Mitigation of Barriers 1 and 3

Suppose that mitigation is undertaken at barriers 1 and 3 (i.e., $x_1 = x_3 = 1$ and $x_2 = 0$). According to the nonlinear model then $z_3 = 1 \times 0.7 \times 1 = 0.7$. Box 1 demonstrates how the linear model produces an equivalent value.

Barrier 1

Based on (2.8): $y_1 \;\leq\; p_1 x_1 \;=\; 0.5 \times 1 \;=\; 0.5 \quad \therefore y_1 \;=\; 0.5$

Based on (2.6): $z_1 \;=\; p_1^0 + y_1 \;=\; 0.5 + 0.5 \;=\; 1$

Barrier 2

Based on (2.8): $y_2 \;\leq\; p_2 x_2 \;=\; 0.3 \times 0 \;=\; 0 \quad \therefore y_2 \;=\; 0$

Based on (2.7): $z_2 \;=\; p_2^0 z_1 + y_2 \;=\; 0.7 \times 1 + 0 \;=\; 0.7$

Barrier 3

Based on (2.8): $y_3 \;\leq\; p_3 x_3 \;=\; 0.8 \times 1 \;=\; 0.8$

Based on (2.9): $y_3 \;\leq\; p_3 z_2 \;=\; 0.8 \times 0.7 = 0.56 \quad \therefore y_3 \;=\; 0.56$

Based on (2.7): $z_3 \;=\; p_3^0 z_2 + y_3 \;=\; 0.2 \times 0.7 + 0.56 \;=\; 0.7$

Box 1: Evaluation of z_3 based (2.6)-(2.9). $y_1 = 0.5$ and $y_3 = 0.56$ as this is a maximization problem and all c_{ij} values are positive costs.

2.5. Case Studies

In order to examine the performance of the linear FPBRP model, barrier datasets were obtained from the US States of Washington and Maine. To provide a benchmark for comparison, the nonlinear version of FPBRP was solved for each dataset and budget combination using the dynamic programming (DP) and greedy add with branch pruning (GABP) algorithms presented in O'Hanley and Tomberlin (2005). The DP formulation is guaranteed to provide an optimal solution to FPBRP, whereas GABP is a heuristic that provides feasible solutions that are not necessarily optimal. A full discussion of these methods is provided in (O'Hanley and Tomberlin, 2005). The linear version of FPBRP presented in Section 2.3.2 was coded in OPL using CPLEX studio version 12.5. The CPLEX model (.mod file) and a data file (.dat file) for the example shown in Figure 1 are provided in the Appendix A. All experiments were run on the same dual-core Toshiba Satellite Pro R850-15F laptop (Intel i3 processor, 2.10 GHz per chip) with 4 GB of RAM.

2.5.1. Washington Dataset

2.5.1.1. Background

In Washington State, culverts are the principal barriers to fish migration, with an estimated 7,700 km of river habitat within the state blocked by such structures (Roni et al., 2002). Information on culverts and other barriers are maintained in the Fish Passage and Diversion Screening Inventory database, including the location of each culvert, an assessment of its current passability by salmonids (between 0 and 1) and an estimate of the repair/replacement cost to restore full passability. O'Hanley and Tomberlin (2005) produced a composite data set (WA4) consisting of a total of 289 culverts located across Water Resource Inventory Areas (WRIAs) 5, 7, 8 and 15, as shown in Figure 2.4. The amount of salmonid habitat above any given barrier is characterized as the river length between the barrier and its immediate upstream barriers or the limits of anadromy. The current amount of accessible habitat (i.e., given a zero budget) is 43.5 km. The total estimated cost of "fixing" of all 289 culverts in WA4 (i.e., increasing passability to 1) is $108.1M. Fixing all 289 culverts results in 250.8 km of accessible habitat. This implies that only 17% of the habitat that could be accessed under no artificial barrier conditions in the WRIAs is currently accessible to diadromous fish.

2.5.1.2. Results

The performance of the CPLEX implementation of FPBRP and the DP and GABP algorithms on the Washington dataset (WA4) is presented in Table 2.2, with time measured in CPU seconds. The "Objective" in Table 2.2 gives the optimal value of the objective function for a given budget amount in terms of maximum connectivity weighted habitat (km) and as a percentage of that accessible under no artificial barrier conditions (% Max). "% Gap" equals the relative difference (as a percentage) and "Diff" equals the absolute difference between the objective value found with GABP and the optimal objective. Table 2.2 reveals the DP and GABP algorithms were extremely efficient, providing solutions at the four budget levels considered within a second. GABP had a maximum optimality gap of just 1.61%. The linear

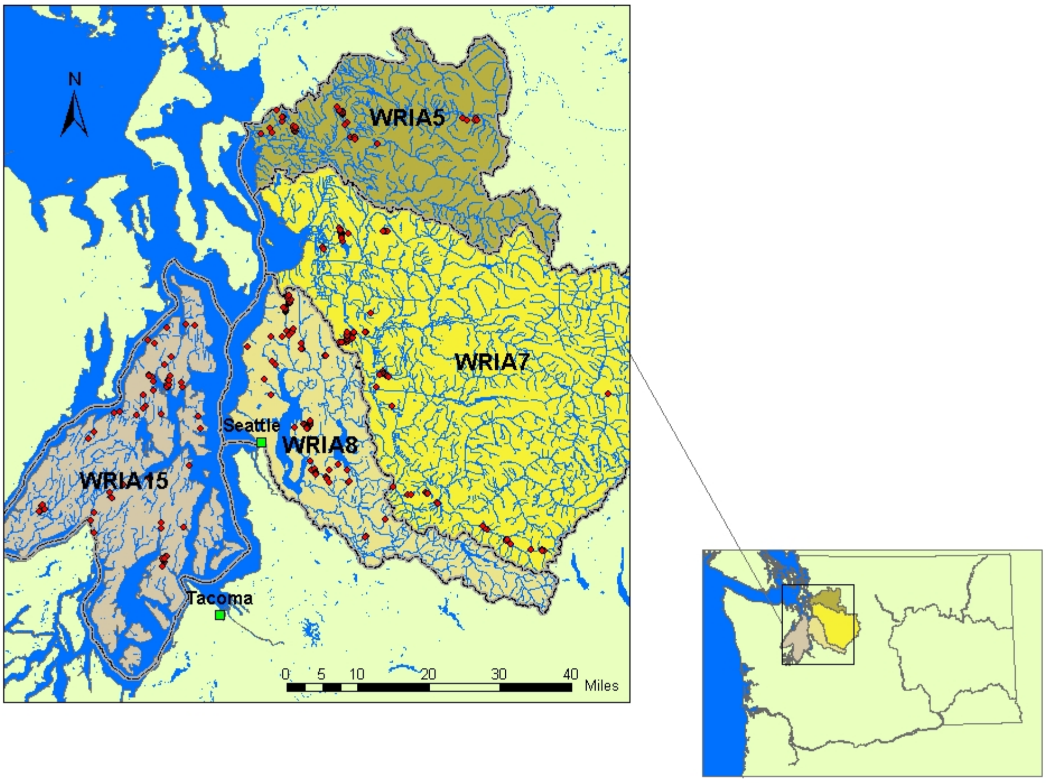


Figure 2.4.: Location and extent of WRIAs 5, 7, 8 and 15 that form dataset WA4. Culverts are represented by small dots. [Taken from O'Hanley and Tomberlin (2005)]

model (CPLEX), although comparatively slower, still produced optimal solutions within just 5 seconds for all budget levels.

As O'Hanley and Tomberlin (2005) identify, a pattern of diminishing marginal improvements in accessible habitat is observed for increasing budget levels with the Washington data set. The general pattern of decreasing returns has also been observed in a number of similar studies (Kuby et al., 2005; Zheng et al., 2009; O'Hanley, 2011). For instance, Table 2.2 shows that a budget of $22M results in a net gain of 146.8 km of river habitat. Increasing this by a further $22M only provides an additional 28.3 km of accessible habitat. This pattern is highlighted by the objective "% Max" results (% of the habitat accessible if no artificial barriers existed). Table 2.2 shows this increases from the current level of 17% to over 50% with a low budget of $5M and over 75% given an investment of $22M. This reveals that a majority of the possible ecological gains can be achieved at relatively low budget levels. Furthermore, this finding implies a relatively small group of barriers are restricting access to the majority of habitat within the WRIAs. The model allows the characteristics of these problem barriers to be investigated, as will be demonstrated in the next case study for watersheds in the U.S. State of Maine.

Table 2.2.: Performance of CPLEX, DP and GABP on the Washington dataset.

Budget	Objective		CPLEX	DP	GABP		
($M)	(km)	(% Max)	Time (s)	Time (s)	Time (s)	% Gap	Diff (km)
5.5	139.2	50.5	3.75	0.06	0.05	0.00	0.0
11.0	164.9	65.8	3.16	0.09	0.02	0.01	0.0
22.0	190.3	75.9	3.95	0.22	0.17	0.69	1.3
33.0	206.5	82.3	4.00	0.31	0.05	0.57	1.2
44.0	218.6	87.2	3.16	0.39	0.13	0.84	1.8
55.0	228.4	91.1	4.15	0.45	0.19	1.08	2.5
66.0	236.4	94.3	3.30	0.50	0.33	1.61	3.8
77.0	242.9	96.9	2.69	0.58	0.16	1.12	2.7
88.0	247.3	98.6	2.93	0.50	0.08	0.34	0.8
Avg			3.45	0.34	0.13	0.70	1.6

2.5.2. Maine Dataset

2.5.2.1. Background

Watersheds in the State of Maine are impacted by numerous artificial barriers, including culverts and both small and large-head dams. In order to assess the problem in a systematic way, the US Fish and Wildlife Service Gulf of Maine Coastal Program has compiled an inventory of barriers across the state, including their location and a qualitative estimate of migratory fish passability. This data set consists of a total of 6,989 natural and artificial barriers, as shown in Figure 2.5. Qualitative passability values (full or partial barrier) were converted into quantitative values (0 and 0.5, respectively). A single mitigation project was considered for each artificial barrier. At small to medium sized dams ($\leq$ 25ft) and culverts, costs were estimated to restore full passability by either dam removal or replacement with a new bottomless arch culvert, respectively. At larger dams (>25 ft) the cost of installing a fish pass with a passability of 0.75 was estimated. The current amount of accessible habitat for the Maine dataset is 1,816.4 km. The cost of fixing all 6,761 artificial barriers is estimated to be $721.9M and results in 23,731.1 km of accessible habitat. Therefore, only 8% of the habitat that could be accessed assuming no artificial barriers in the Maine watersheds is currently accessible to diadromous fish.

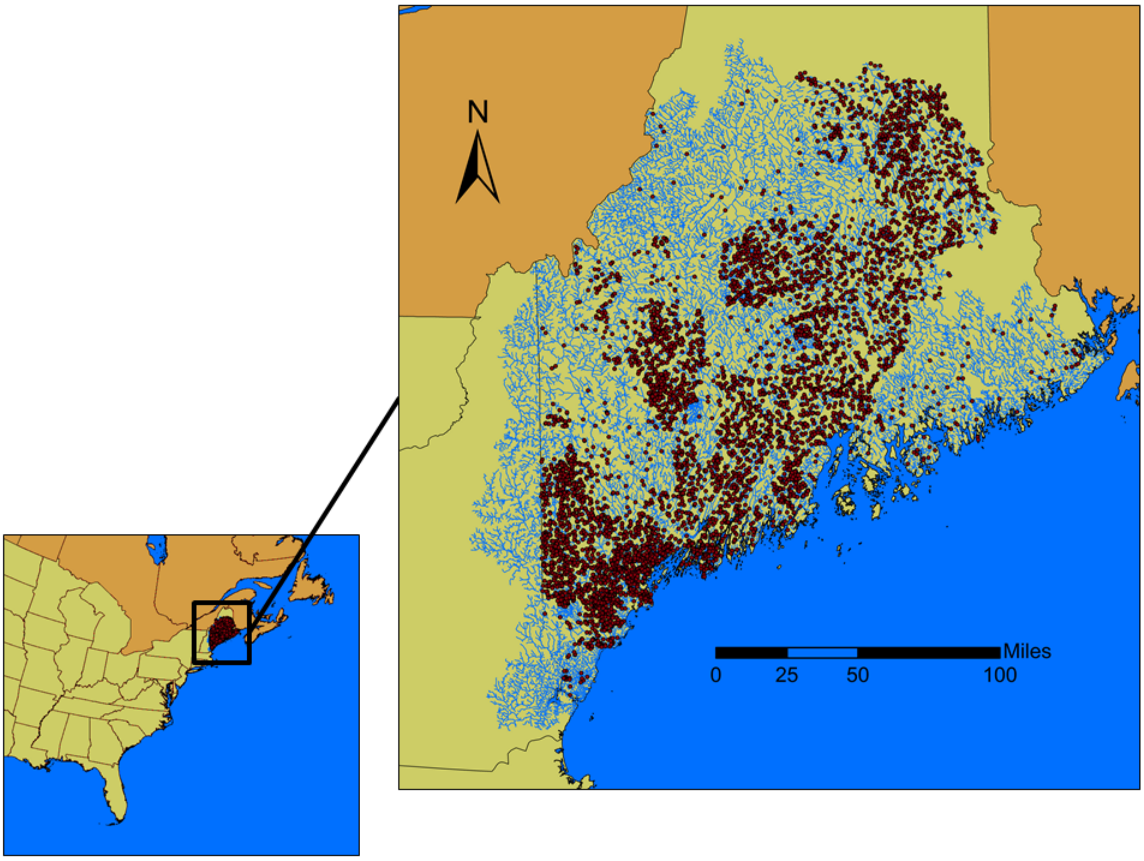


Figure 2.5.: Location of artificial and natural barriers (represented by small dots) across the State of Maine.

2.5.2.2. Results

The performance of the CPLEX implementation of FPBRP and the DP and GABP algorithms on the Maine dataset is provided in Table 2.3. For large datasets such as this, solving the DP algorithm becomes ever more computationally intensive as the number of barriers and possible divisions of the budget (sub-problems) rise. Above a certain budget the number of sub-problems to solve reaches a threshold where the overall the problem becomes intractable and the DP algorithm fails. This threshold was reached at a budget level of between \$20M and \$25M on the computer used to run the experiments.

Table 2.3 identifies the DP algorithm as being highly efficient at low budget levels ($\leq$\$20M), in which case it is able to find optimal solutions within 2 seconds. Above the \$20M threshold, however, DP could not provide any solution. GABP, by contrast, was able to return near optimal solutions within 7 to 180 seconds. The optimality gap for the GABP heuristic is generally small at the higher budget levels ($>$\$20M), with a maximum gap of only 0.33% (71.8 km) at \$300M. For lower budget levels ($\leq$\$20M), the optimality gap reached a maximum of 1.50% (161.1 km) at

$15M. Whilst less efficient than the DP algorithm at lower budget levels, the CPLEX implementation was, nonetheless, able to return optimal solutions within 40 seconds for *all* budget levels. For both the GABP heuristic and the CPLEX implementation the longest times to return a good feasible or optimal solution where encountered at the mid budget amount ($300M). The time to return a solution decreased with increasing budget at $450M and above as solutions became increasingly nested and the number of possibilities (i.e., which barrier not to fix) decreased. A final observation on the CPLEX implementation is that it consistently out performed the GABP heuristic in terms of solution quality and time at budget levels of $50M and higher. This is a key finding as it means that not only is the linear model capable of providing optimal solutions for large datasets approaching 7,000 barriers, but it also provides them quicker than the GABP heuristic.

Table 2.3.: Performance of CPLEX, DP and GABP on the Maine dataset.

Budget	Objective	Objective	CPLEX	DP*	GABP		
			Time	Time	Time	%	Diff
($M)	(km)	(% Max)	(s)	(s)	(s)	Gap	(km)
5	8,133.5	34.3	9.70	0.50	1.47	1.10	89.1
10	9,804.5	41.3	11.27	0.70	2.84	0.26	25.4
15	10,781.1	45.4	8.75	0.89	5.84	1.50	161.6
20	11,547.8	48.7	10.35	1.31	12.29	0.16	18.9
25	12,172.0	51.3	10.67	-	6.86	0.32	39.1
50	14,337.0	60.4	12.63	-	28.10	0.14	20.4
100	17,074.6	72.0	12.52	-	79.65	0.21	35.2
150	18,882.8	79.6	15.56	-	108.45	0.31	57.9
300	21,690.3	91.4	39.71	-	179.65	0.33	71.8
450	23,077.2	97.2	36.11	-	138.28	0.09	20.9
600	23,711.3	99.9	16.92	-	123.27	0.04	9.9
Avg			16.74	-	62.43	0.41	50.0

* A "-" indicates that the DP algorithm was unable to obtain a solution at the specified budget level.

Again a pattern of diminishing marginal improvements in accessible habitat with increasing budget is observed for the Maine dataset. This is illustrated in Figure 2.6, which shows the optimal value of maximum accessible habitat varies with budget.[1] Figure 2.6 reveals that substantial gains in accessible habitat are delivered with modest investments ($5-10M) and small increases in accessible habitat are delivered when moving up to larger levels of investment (e.g., $300M to $450M). The percentage of the amount of habitat that would be accessible assuming no artificial barriers in the Maine watersheds (% Max) can be increased from its current level

[1] It should be noted that this curve is not continuous but comprises of a series of step-wise increments at fine scale. This implies thresholds for investment exist at which sufficient budget becomes available to mitigate a further barrier.

of 8% to over 50% with a low budget of \$25M and to over 70% with a relatively modest budget of \$100M. These budgets are only 3.5% and 15% of the total amount required to mitigate all candidate barriers in the Maine watersheds. This, again, implies there are a relatively small number of problematic barriers. This is explored further in Table 2.4, which shows the characteristics of the barriers that are selected for mitigation action under the different budget solutions.

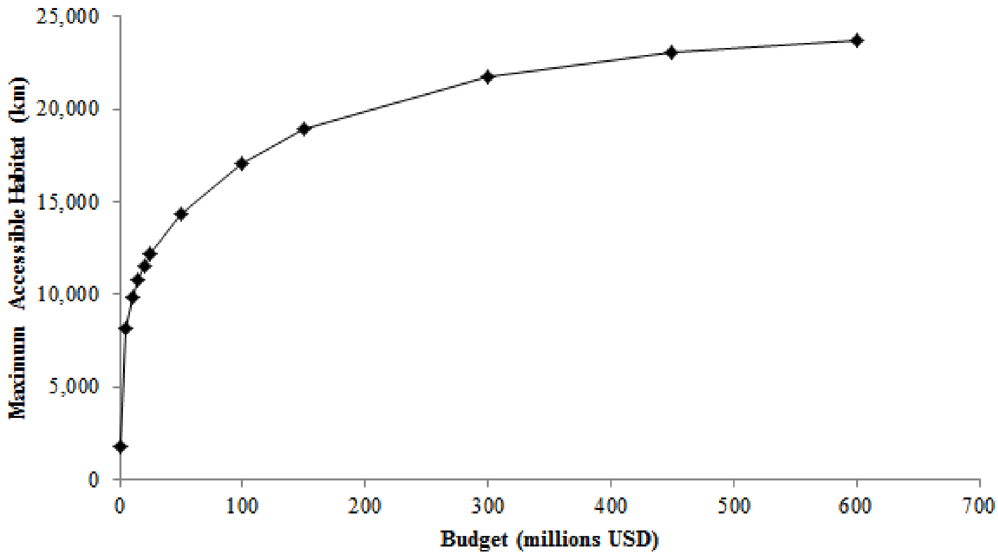


Figure 2.6.: Maximum accessible habitat versus budget for the Maine dataset.

The "All Barriers" column in Table 2.4 provides the breakdown, by characteristics, of the 6,761 candidate barriers for mitigation in the Maine dataset. The "Solution" columns show the number of each barrier type that is mitigated under the optimal solution for the stated budget level. Average values for selected properties of the barriers in these respective solution sets is provided at the bottom of the table.The first observation that can be made with respect to Table 2.4 is that only 294 (4.3%) of the barriers in the Maine dataset are mitigated in the \$25M solution, where over 50% of the maximum possible accessible habitat is achieved. This confirms a small set of particularly problematic barriers exists. Table 2.4 shows these are typically the barriers towards the base of large river networks, as revealed by the high average number of upstream barriers and USL values for barriers that are selected under low budget solutions (i.e., $\leq$\$25M).

Table 2.4 also reveals barriers retaining the greatest amount of unimpeded river habitat (v_j) are also priorities for mitigation at low budgets levels. Whilst these results are intuitive, this type of analysis quantifies the magnitude of the effect a small number of such barriers has on habitat accessibility at the state or regional scale. As the solutions generated are prescriptive, these 'problem' barriers can be readily identified and scheduled for mitigation action. Given Table 2.4 clearly shows

Table 2.4.: Analysis of river barrier mitigation solutions for the Maine dataset.

	All	Solution (budget $M)										
	Barriers	5	10	15	20	25	50	100	150	300	450	600
Total	6,761	33	86	125	216	294	647	1,534	2,559	4,693	5,011	6,033
Barrier types												
Culvert	6,015	3	23	43	115	174	470	1,287	2,267	4,255	4,502	5,421
Small Dam ($\leq$ 25ft)	688	30	63	81	100	119	171	237	280	416	476	567
Large Dam ($>$ 25ft)	58	0	0	1	1	1	6	10	12	22	33	45
Full Barrier	2,805	21	60	89	159	215	453	879	1,219	1,938	2,079	2,476
Partial Barrier	3,956	12	26	36	57	79	194	655	1,340	2,755	2,932	3,557
Average												
Cost (US $1,000)	106.78	151.5	116.3	120.0	92.6	85.0	77.3	65.2	58.6	63.9	89.8	99.5
v_j (km)	6.2	184.7	91.4	73.4	46.2	36.3	21.9	11.7	7.9	5.4	6.1	5.6
USL (km)	44.4	1,932.6	828.5	609.7	371.1	278.6	232.4	104.8	65.2	45.7	51.8	46.9
No. DS Bars	5.4	2.8	2.4	2.3	2.4	2.4	3.0	3.3	3.7	4.3	4.4	5.0
No. US Bars	5.3	322.9	143.4	101.8	63.2	47.8	31.33	14.4	9.4	6.6	6.4	5.8

Cost is the cost of barrier mitigation, v_j is the length of habitat a barrier retains, USL is the total length of river above a barrier to the limits of the system, No. DS Bars and No. US Bars are the number of downstream and upstream barriers respectively.

a disproportionately high number of small dams are prioritized under low budget solutions, targeting these is likely to be an acceptable ’rule of thumb’ for barrier mitigation in Maine watersheds.

Table 2.4 shows that 4,693 (nearly 70%) of all candidate barriers in the Maine watersheds are mitigated under the \$300M solution, which delivers over 90% of the maximum possible accessible habitat at only 40% of the maximum budget. This implies the existence of a number of expensive to mitigate barriers that are not substantially restricting habitat access for migratory fish, as revealed by the increasing average costs encountered above \$300M. Table 2.4 also shows only a single expensive large head barrier is selected for mitigation action under the \$25M solution and none under the \$10M solution, suggesting these dams are not the main drivers of connectivity issues within the Maine watersheds. A final observation that can be made is that the optimization model generally targets full barriers over partial ones.

2.6. Conclusions

The ecological integrity of river systems across the world has been negatively impacted as the result of fragmentation by artificial river barriers like dams, weirs and culverts. The negative effects of multiple barriers on diadromous fish species, such as salmon, are well documented. Consequently, barrier mitigation is increasingly employed in river restoration to improve the connectivity of fluvial ecosystems. This chapter presents a linear version of the Fish Passage Barrier Removal Problem (FPBRP) for optimizing barrier mitigation decisions. The chapter contributes to the existing literature by providing a framework for identifying cost-effective solutions to tackle the ecological impacts of river infrastructure that is highly efficient, scalable and can be readily implemented using off-the-shelf optimization software.

As Kemp and O’Hanley (2010) discuss, techniques that deliver optimal solutions offer potentially substantial benefits over traditional methods like scoring and ranking. Given that longitudinal connectivity is critical to the ecological integrity of fluvial ecosystems, explicitly considering this in the modeling framework presented serves to generate holistic solutions that can benefit many aquatics species in addition to migratory fish (Padgham and Webb, 2010). Moreover, the ability to readily obtain prescriptive solutions that maximize accessible river habitat highlights the advantage of optimization frameworks compared to graph theoretic approaches, particularly when analyzing realistically sized datasets.

The computational efficiency of the linear FPBRP is demonstrated using real data from the US states of Washington and Maine. The model consistently provided optimal barrier mitigation solutions at various budget levels for both datasets within seconds. The model can also prove insightful to watershed managers by clarifying how potential habitat gain varies with different levels of investment. Pareto-optimal trade-off curves, such as Figure 2.6, can be constructed to identify levels of investment that deliver high environmental returns at suitable cost (O'Hanley, 2011). In this regard, the analysis presented reveals that substantial ecological gains for migratory fish species can be gained in the two case study areas at low investment levels, confirming barrier mitigation as a cost-effective river restoration option. Barriers towards the base of large networks that retain substantial amounts of unimpeded river habitat are found to be most problematic to migratory fish. The analysis reveals that a relatively small set of such barriers can be the main drivers of regional connectivity issues. For the Maine case study a disproportionately large number of these barriers are identified as small dams, rather than large dams or culverts. Given the prescriptive nature of the solutions generated, these barriers can be readily identified and targeted for mitigation action.

Employing optimization models such as the one presented here is vitally important if river restoration goals are to be achieved in a cost-effective manner. As such, it is anticipated the linear FPBRP will be of direct benefit to practitioners involved in river barrier mitigation. The natural extension to this work is to formulate a linear model that accounts for the needs of resident fish. Chapter 3 presents research in this regard.

3. A Toolkit for Optimizing for Resident Fish Passage Barrier Mitigation Actions

3.1. Abstract

The widespread presence of river barrier infrastructure across the world compromises longitudinal connectivity in river systems, reducing both fish abundance and diversity. Accordingly, the improvement of barrier passability is critical to successful river restoration.This chapter presents a novel mixed integer linear programming (MILP) model for optimizing barrier mitigation actions aimed at improving longitudinal connectivity for resident fish species. A longitudinal connectivity metric is incorporated into the optimization model by allowing barriers to be considered partially passable. Whilst this normally introduces non-linearity into the problem, a linear model is formulated using the method of *probability chains*. In addition an extension of the model is presented that can be used in conjunction with statistical approaches to maximize estimated gains in fish species richness. Both models can be readily implemented using off-the-shelf optimization software. The methods are demonstrated using a case study river in the South East of England. The optimization model is shown to be more efficient than existing methods and highly scalable. For the case study, large steady returns in ecological gains are encountered up to moderate levels of investment. Analysis reveals that it is the larger, low passability barriers with higher mitigation costs located in the main river stem, higher Strahler order reaches or areas of dense river branching that are generally prioritized for mitigation action.

3.2. Introduction

Hydrological connectivity is essential to the ecological integrity of fluvial ecosystems (Pringle, 2003). However, human societies have extensively modified river systems across the globe in order to provide socioeconomic benefits such as water supply, flood suppression, power generation and transportation. Obtaining these benefits typically involves the construction of structures (barriers) that fragment the continuity of rivers and substantially alter their natural flow, thereby transforming the biological, morphological and physio-chemical characteristics of rivers and their associated ecosystems (Bednarek, 2001). The presence of physical obstructions to fish can also reduce or eliminate their ability to access essential habitats and resources, affecting distribution, population structure, spawning success and recruitment (Nunn and Cowx, 2012). Furthermore, as a result of physical fragmentation, the dispersal ability of resident fish populations is restricted. This can result in the isolation of local populations from catchment meta-populations, which, in turn, can lead to genetic change and local extinctions as re-population is no longer possible (Stanford et al., 1996; Wofford et al., 2005).

While large head dams present major obstacles, the cumulative effect of low head dams, road crossings and other small barriers can also be significant (Roni et al., 2002; de Leaniz, 2008; Lucas et al., 2009; Nunn and Cowx, 2012; Januchowski-Hartley et al., 2013). Numerous studies have demonstrated the negative effects small artificial barriers have on both migratory (Sheer and Steel, 2006; Catalano et al., 2007; Lucas et al., 2009) and resident fish populations (Nislow et al., 2011; Letcher et al., 2007). Removing fish passage barriers has been demonstrated to deliver increased fish density (Gardner et al., 2013), diversity (Catalano et al., 2007) and rapid colonization of stream reaches (Roni et al., 2008). Consequently, river barrier mitigation is identified as one of the most cost-effective means of improving fish populations at the catchment scale (Roni et al., 2002). Furthermore, where river barriers compromise the ecological potential of rivers, there are often legislative drivers for improving longitudinal connectivity, such as the Water Framework Directive in the EU and the Endangered Species Act in the US.

Given the increasing interest in barrier mitigation as part of river restoration efforts, a variety of methodologies have emerged in order to cost-effectively prioritize mitigation actions. Scoring and ranking of barriers has been the most commonly employed technique (e.g., Kocovsky et al., 2009; Nunn and Cowx, 2012). However, scoring and ranking approaches consider each barrier independently and typically result in sub-optimal portfolios of barriers being targeted for action (Kemp and O'Hanley, 2010). Optimization models provide a framework for decision making that guarantees the achievement of maximum benefit given available resources by considering all barriers within a river network collectively (O'Hanley and Tomberlin, 2005).

Existing optimization models for barrier mitigation all characterize rivers as dendritic ecological networks (DENs), in which rivers are assumed to have a branching architecture with branches increasing in number and decreasing in size as one moves up the system (Grant et al., 2007). An example river system and associated DEN is provided in Figure 3.1. The model will seek to maximize an objective (say accessible habitat) subject to a set of constraints, such as a budget. For example, Paulsen and Wernstedt (1995), Kuby et al. (2005), Zheng et al. (2009), Zheng and Hobbs (2013) all formulate their optimization models as mixed integer linear programs (MILPs), where the primary decision variables are whether to remove a barrier or not. These models are constrained to require mitigation of all barriers downstream of any candidate barrier to the river mouth and so are designed specifically to facilitate upstream migration. This reflects the observation by Kemp and O'Hanley (2010) that barrier assessment typically focuses on diadromous fish species that migrate between freshwater and ocean habitats due to the economic importance of such fish. Two exceptions are noted in the literature. O'Hanley (2011) presents a model that maximizes the single largest section of river, while O'Hanley et al. (2013b) propose a model that maximizes accessible habitat for resident fish species based on longitudinal connectivity metrics.

Typically, the optimization models presented in the literature follow the approach of specifying the initial and post-mitigation barrier passabilities as being binary (e.g., Paulsen and Wernstedt, 1995; Kuby et al., 2005; Zheng et al., 2009; O'Hanley, 2011; Zheng and Hobbs, 2013). This approach is useful from an applied perspective as it limits the data requirements for specifying the varying effect of barriers on fish passability. It also makes the optimization models easier to solve by maintaining a simple linear structure. Specifying barriers as partially passable, on the other hand, is generally more realistic but often requires expert judgment of fisheries biologists and can be time consuming and expensive (O'Hanley, 2011). However, the emergence of standardized rapid in-field assessment methodologies (such as the one proposed by Nunn and Cowx (2012) for migratory fish species) can be employed to mitigate this to a degree. Incorporating partial passability is also challenging from a modeling perspective. It requires calculation of the cumulative probability of a fish successfully negotiating a series of partial barriers as it moves through the river system (i.e., the product of barriers passabilities). This makes the problem non-linear. For example, O'Hanley and Tomberlin (2005) present a model in which they specify cumulative passability to habitat immediately above any barrier as the product of the passabilities of all the intervening downstream barriers to the river mouth. In order to solve the model they rely on specialist dynamic programming and heuristic algorithms. However, this can be overcome using the linearization technique developed in O'Hanley et al. (2013b), as presented for the case of diadromous fish in Chapter 2.

Connectivity within river systems is determined by the passabilities and relative positions of all the barriers within the catchment (Diebel et al., 2014). Given the interest in ameliorating the effects of habitat fragmentation in rivers, a number of connectivity indices have been proposed in order to assess the impact of barriers on longitudinal connectivity (e.g., Cote et al. (2009); McKay et al. (2013); Diebel et al. (2014)). In this regard, O'Hanley and Tomberlin (2005) approach is well suited to characterizing connectivity for diadromous fish that follow a simple migration path up and down the river system from the river mouth. However, more general approaches are required for resident fish species, as their movement patterns will be more complex given they may journey between any pair of inter-barrier subnetworks in the river system. Accordingly, Cote et al. (2009) describe the Dendritic Connectivity Index (DCI) that calculates the average connectivity of all inter-barrier river segments with each other. Diebel et al. (2014) present a more general connectivity metric (the C metric), which further accounts for multiple habitat types and the travel distance between habitat areas. The appeal of the C metric is it can capture the relative benefits of accessing particular habitat types that may promote recolonization and genetic exchange, provide refuge or be particularly suited for given life-cycle stages (Diebel et al., 2014).

These connectivity metrics are useful benchmarks for assessing barrier mitigation strategies as the relative benefit of mitigating given barriers within river systems can be explored by evaluating the impact on DCI or the C metric. O'Hanley et al. (2013b), present a MILP model that maximizes available habitat for resident fish species as determined by the C metric. This is believed to be the only example of an optimization model in the literature that specifically considers the needs of residential fish while considering partial barrier passability. O'Hanley et al. (2013b) demonstrate the application of the model to a case-study area (the Pine-Poppel catchment in Wisconsin, USA) containing 130 artificial and natural barriers.

This chapter presents an efficient *linear* model for optimizing river barrier mitigation decisions in order to maximize the amount of accessible habitat for residential fish. Specifically, the Resident - Fish Passage Barrier Removal Problem (R-FPBRP) model proposed by O'Hanley et al. (2013b) is reformulated using a newly proposed technique of forming probability chains to evaluate cumulative passability terms (O'Hanley et al., 2013a). This increases the efficiency and scalability of the model and simplifies its implementation. This chapter also shows how the R-FPBRP model can be extended to provide estimates of net average fish species gains using fish population survey data. These optimization models are then demonstrated using the River Wey in South East England as a case study. The remainder of the chapter is organized as follows. Section 3.3 presents the optimization models. In Section 3.4, the methods are demonstrated using the case study river. Section 3.5 provides concluding remarks. The techniques presented in this paper are anticipated to be of direct use to practitioners involved in catchment management.

3.3. The Resident Fish Passage Barrier Removal Problem (R-FPBRP)

3.3.1. The R-FPBRP Model

The aim of the R-FPBRP is to select barriers for repair or removal (i.e., mitigation) within a river system in order to maximize the amount of accessible habitat for resident fish. Figure 3.1(a), provides an example of a river network containing several barriers as a simple map. Figure 3.1(b) provides an equivalent dendritic ecological network (DEN). In the R-FPBRP areas above a barrier up to the next set of barriers or the ends of the river are termed "subnetworks". These inter-barrier subnetworks within the system are defined by their downstream barrier j. For instance, the subnetwork for barrier A in Figure 3.1(a) is all habitat above A up to barriers B and C. In Figure 3.1(a), the bidirectional passability p_j^0 of each barrier j and the amount of river habitat v_j in the subnetwork above that barrier is also provided. These barrier passabilities can take on fractional values in the range 0 to 1. The bidirectional passability p_j^0 represents the probability that fish are able to pass a particular barrier j in both the upstream and downstream directions (i.e., upstream passability multiplied by downstream passability). For example, with respect to barrier B in Figure 3.1a, the passability in the upstream direction is 0.5 and the passability in the downstream direction is 0.8. Therefore, parameter $p_B^0 = 0.4$. Barrier 'M' is the river mouth, which is represented as a dummy barrier (i.e., $p_j^0 = 1$) in order to ensure that all habitat in the river system is captured in the DEN.

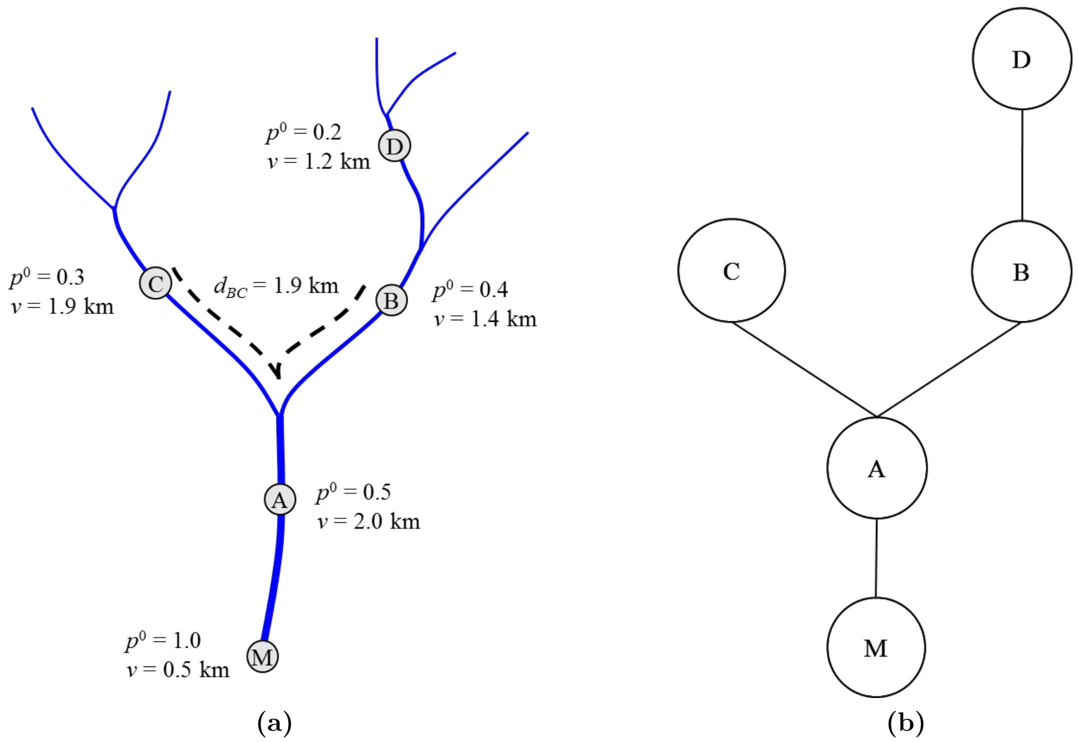


Figure 3.1.: Example of a river barrier network represented as (a) a simple map and (b) as an equivalent dendritic ecological network (DEN).

The cumulative passability z_{jk} between habitat in an origin subnetwork j and a destination subnetwork $k \neq j$ is taken as the product of the bidirectional passability of the intervening barriers that must be negotiated on the journey from subnetwork j to k. For instance, fish accessing habitat in subnetwork C starting from subnetwork B (Figure 3.1a) must negotiate barriers B and C in both directions to complete a return journey. Consequently, the cumulative passability of this route z_{BC} is the product of the bidirectional passability of these barriers (i.e. $z_{BC} = 0.4 \text{ x } 0.3 = 0.12$).

The distance of this route (d_{BC}= 1.9km) is also shown in Figure 3.1a. Cumulative passability along a given route can be considered analogous to the longitudinal connectivity between the origin and destination subnetworks for that route.

The number of possible journeys that fish could conceivably make within a river system fragmented by n barriers is based on the premise a fish could originate in any of the n inter-barrier subnetworks in the system and make a return journey to any of the $n-1$ other subnetworks within the system. A symmetry assumption is employed, implying that a return journey between between any two subnetworks is the same regardless of which subnetwork a fish begins its journey from. Therefore, a total of $\frac{n(n-1)}{2}$ unique routes will exist. The R-FPBRP seeks to maximize habitat accessibility across the river system as a whole by increasing the cumulative passability of routes via barrier mitigation actions. In order to consider all habitat in the river system, a dummy barrier with passability equal to 1 must be introduced at the river mouth if no such structure exists (e.g., barrier M in Figure 3.1). The model assumes that multiple mitigation options (e.g., removal, replacement, fitting baffles, installing fish passes) may be available at any given barrier with varying cost and passability improvements but that only one project can be carried out at any given barrier. Lastly, there is assumed to be a budget, which limits total expenditure on river barrier mitigation action.

3.3.2. The *C* metric

Given the interest in river fragmentation a number of metrics are identified in the literature for measuring longitudinal habitat connectivity within catchments (as reviewed in Section 3.2). In general, all these metrics are amiable to being employed in optimization models seeking to maximize the amount of connectivity weighted habitat within catchments. However, metrics that characterize connectivity based on access from the river mouth (e.g., the HCIU proposed by McKay et al., 2013) are not suitable for maximizing habitat accessibility for resident fish species. Accordingly, the optimization models presented here employ a connectivity metric formulated to capture the requirements of resident fish, specifically the C metric proposed by Diebel et al. (2014). The advantages of the C metric are its ability to account for multiple habitat types and also the travel distance between habitat areas. This is not provided by the other connectivity metrics identified in the literature (e.g., the DCI_p presented by Cote et al., 2009). Consequently, employing the C metric allows a more general optimization model to be developed that can capture the relative benefits of accessing particular habitat types that may promote recolonization and genetic exchange, provide refugia or be particularly suited for given life-cycle stages (Diebel et al., 2014). An explanation of how the C metric is calculated is provided below.

Using the notation provided in Table 3.1, the C Metric is constructed by first calculating the total availability A_{jh} of habitat type h accessible from a given river subnetwork j, as follows:

$$A_{jh} = \sum_{k \in J} D_{jk} v_{kh} z_{jk}$$

Table 3.1.: Notation used in the C metric.

Symbol	Definition
J	Set of all inter-barrier river subnetworks, indexed by j and k
H	Set of habitat types within the catchment, indexed by h having cardinality m
v_{kh}	Amount of habitat type h in subnetwork k
v_j	Amount of habitat in subnetwork j
z_{jk}	The product of the bidirectional passabilities of all barriers traversed when traveling from subnetwork j to subnetwork k and back again
d_{jk}	Distance for route between subnetworks j and k
d'	Dispersal distance of focal fish species / guild

The baseline availability A^0_{jh} of habitat type h accessible from subnetwork j assuming no barriers exist in the river network is defined as:

$$A^0_{jh} = \sum_{k \in J} D_{jk} v_{kh}$$

The D_{jk} term employed in the calculation of A_{jh} and A^0_{jh} represents an inverse distance weighted dispersal factor for the journey between subnetworks j and k. D_{jk} is defined as:

$$D_{jk} = \frac{1}{1 + \left(\frac{d_{jk}}{d'}\right)^2}$$

The connectivity C_j for a given subnetwork j can be calculated as follows:

$$C_j = \frac{1}{m} \sum_{h=1}^{m} \frac{A_{jh}}{A^0_{jh}} \tag{3.1}$$

Consequently, a measure of the overall connectivity weighted habitat $\bar{H}$ within the catchment is given by:

$$\bar{H} = \sum_{j \in J} v_j C_j \qquad \forall j \in J \tag{3.2}$$

3.3.3. Accessible Habitat Model Formulation (R-FPBRP Model)

In order to formulate R-FPBRP, the notation provided in Table 3.1 and 3.2 is employed. Some of this notation was introduced previously in Table 2.1, Chapter but is repeated in full here for convenience and clarity. In addition, the following decision and associated passability variables are employed:

$$x_{ji} = \begin{cases} 1 & \text{if mitigation project } i \text{ is implemented at barrier } j \\ 0 & \text{otherwise} \end{cases}$$

$$y_{jki} = \begin{matrix} \text{increase in cummulative passability between origin subnetwork } j \\ \text{and destination subnetwork } k \text{given implementation of project } i \\ \text{at the last barrier to be traversed before arriving at subnetwork } k \end{matrix}$$

In addition the following parameter is defined:

$$v^0_{jh} = \sum_{k \in J} D_{jk} v_{kh} \tag{3.3}$$

Where v^0_{jh} the amount of inverse distance weighted habitat of type h in the catchment that is accessible from subnetwork j assuming there are no barriers to fish movement.

Table 3.2.: Additional notation used in R-FPBRP.

Symbol	Definition
J	Set of all barriers, indexed by j and k
A	Set of all mitigation projects available indexed by i
A_j	Set of all mitigation projects available at barrier j
J^*	Set of barriers for which at least one mitigation project exists (i.e., $\lvert A_j \rvert \geq 0$) indexed by j
Γ_j	Set of subnetworks directly adjacent to j
b	Available budget for carrying out mitigation actions
c_{ji}	Cost of implementing mitigation project i at barrier j
p^0_j	Initial bidirectional passability of barrier j (upstream passability x downstream passability)
p_{ji}	Increase in passability at barrier j given implementation of mitigation project i
$f(j,k)$	Final barrier to be passed on route from subnetwork j to k
$\ell(j,k)$	The last (a.k.a. linking) subnetwork to be traversed on route from subnetwork j to k

The formulation for R-FPBRP is then given as follows:

$$\text{R}-\text{FPBRP} \;\; \max \;\; \underbrace{\sum_{j}\sum_{k>j}\frac{1}{m}D_{jk}\left(v_j\sum_{h=1}^{m}\frac{v_{kh}}{v_{jh}^{0}}+v_k\sum_{h=1}^{m}\frac{v_{jh}}{v_{kh}^{0}}\right)z_{jk}}_{(i)} \;+\; \underbrace{\sum_{j}\frac{1}{m}v_j\sum_{h=1}^{m}\frac{v_{jh}}{v_{jh}^{0}}z_{jj}}_{(ii)} \tag{3.4}$$

$s.t.$

$$z_{jk} = p^0_{f(j,k)} + \sum_{i\in A_{f(j,k)}} y_{jki} \qquad \forall j,\, k\in J \mid k>j,\; k\in\Gamma_j \tag{3.5}$$

$$z_{jk} = p^0_{f(j,k)}\, z_{j\ell(j,k)} + \sum_{i\in A_{f(j,k)}} y_{jki} \qquad \forall j,\, k\in J \mid k>j,\; k\notin\Gamma_j \tag{3.6}$$

$$y_{jki} \le p_{f(j,k)i}\, x_{ji} \qquad \forall j,\, k\in J \mid k>j,\; f(j,k)\in J^*,\; i\in A_{f(j,k)} \tag{3.7}$$

$$y_{jki} \le p_{f(j,k)i}\, z_{j\ell(j,k)} \qquad \forall j,\, k\in J \mid k>j,\; f(j,k)*\in J^*\,, k\notin\Gamma_j,\; i\in A_{f(j,k)} \tag{3.8}$$

$$z_{jj} = 1 \qquad \forall j\in J \tag{3.9}$$

$$\sum_{i\in A_j} x_{ji} \le 1 \qquad \forall j\in J^* \tag{3.10}$$

$$\sum_{j\in J^*}\sum_{i\in A_j} c_{ji}x_{ji} \le b \qquad \forall j\in J^* \tag{3.11}$$

$$x_{ji}\in\{0,1\} \qquad \forall i\in A_j \tag{3.12}$$

$$z_{jk}\;\text{ free variable} \qquad \forall j,\, k\in J \mid k>j \tag{3.13}$$

$$y_{jki}\;\text{ free variable} \qquad \forall j,\, k\in J \mid k>j,\; i\in A_{f(j,k)} \tag{3.14}$$

The objective (3.4), which is entirely equivalent to (3.2), is split into two component parts. The first part (3.4i) calculates the connectivity and distance weighted habitat accessed via all the possible inter-subnetwork routes. The second part (3.4ii) considers habitat accessed via all the possible intra-subnetwork routes. This provides a normalized summed measure of all the subnetwork habitat amounts as a proportion of the total habitat within the system. By definition, the cumulative passability for intra-subnetwork routes z_{jj} is equal to 1 as no barriers need to be negotiated.

Collectively, variables z_{jk} and y_{jki} and constraints (3.5)-(3.9) form what is known as a “probability chain” (O’Hanley et al., 2013a). Probability chains are used to iteratively calculate cumulative passability between any two subnetworks j and k. Specifically, equations (3.5) ensure that the cumulative passability between adjacent subnetworks (i.e., separated by only a single barrier) is equal to the initial bidirectional passability of the separating barrier $p^0_{f(j,k)}$ plus any increase in bidirectional passability y_{jki} due to mitigation at that barrier. Equations (3.6) ensure that the cumulative passability between subnetworks that are separated by more than one barrier is equal to the cumulative passability $z_{jl(j,k)}$ between the origin subnetwork j and the subnetwork reached immediately before the destination subnetwork $\ell(j,k)$ multiplied by the bidirectional passability of the last barrier to be negotiated $p^0_{f(j,k)}$ plus any increase in cumulative passability y_{jki} from mitigating that barrier. Mitigation action is only considered for the final barrier $f(j,k)$ traversed along the route from j to k as the effect of mitigating other barriers along the route is captured via the $z_{j\ell(j,k)}$ term. Inequalities (3.7) specify that y_{jki} must equal 0 when no mitigation is undertaken at the final barrier along the route from j to k (i.e., $x_{ji} = 0$). If project i is selected, then y_{jki} is bounded from above by $p_{f(j,k)i}$, the increase in cumulative passability from implementing project i. Inequalities (3.8) limit the increase in cumulative passability for journeys separated by more than one barrier to be no more than the increase in bidirectional passability $p_{f(j,k)i}$ given the implementation of project i at barrier $f(j,k)$ multiplied by the cumulative passability $z_{j\ell(j,k)}$ between the origin subnetwork j and subnetwork $\ell(j,k)$, which is reached immediately before the destination subnetwork k. Equations (3.9) ensure that there is full passability for all intra-subnetwork routes. Constraints (3.5)-(3.9) are similar to constraints (2.6) - (2.9) of the FPBRP presented in Chapter 2, except that instead of propagating a probability chain up the river system form the river mouth they propagate a probability chain from any originating subnetwork to the subnetworks elsewhere in the river system.

Constraints (3.10) ensure only one mitigation project i can be carried out at any given artificial barrier. Inequality (3.11) stipulates that the total cost of barrier mitigation actions cannot exceed the total available budget b. Constraints (3.12) impose binary restrictions on the x_{ji} decision variables. Inequalities (3.13) and (3.14) indicate that z_{jk} and y_{jki} are free variables. An illustrative example of the probability chain application in the context of cumulative fish barrier passage is provided in Chapter 2.

3.3.4. Net Species Gain Model Formulation (R-FPBRP(S) Model)

The R-FPBRP model maximizes for the amount of connectivity weighted river habitat. However, in some circumstances, river managers may wish to maximize fish species richness within a catchment. Where sufficient fish survey data exist, the relationship between a subnetworks current C metric value C_j^0 and fish species richness R_j can be empirically estimated using standard statistical techniques. Accordingly, a statistical model of the general form $R_j = \alpha + \beta_1 C_j^0 + \varepsilon$ allows the regression coefficient β_1 on C_j^0 for estimating R_j to be recovered. The R-FPBRP model can, in turn, be modified to maximize net gains in average fish species richness. In order to formulate this revised model (R-FPBRP(S)), the following additional variables are introduced:

V = total amount of habitat within the river system

β_1 = regression coefficeint on $C_j^0$for estimating R_j

$\triangle C_j$ = change in connectivity of subnetwork j

The R-FPBRP(S) model is formed by replacing the objective (3.4) in R-FPBRP with the following objective (3.15) and adding equations (3.16):

$$\mathrm{R-FPBRP(S)}\ \max \frac{1}{V}\sum_j v_j \beta_1 \triangle C_j \tag{3.15}$$

s.t. (3.5)-(3.14) and the following:

$$\triangle C_j = \sum_{k>j} \frac{1}{m} D_{jk} \left(\sum_{h=1}^{m} \frac{v_{kh}}{v_{jh}^0} + \sum_{h=1}^{m} \frac{v_{jh}}{v_{kh}^0} \right) z_{jk} + \frac{1}{m} \sum_{h=1}^{m} \frac{v_{jh}}{v_{jh}^0} z_{jj} - C_j^0 \qquad \forall j \in J \tag{3.16}$$

The R-FPBRP(S) objective (3.15) maximizes the habitat weighted average of net fish species richness gain across all subnetworks in the river system following barrier mitigation. The change in C metric connectivity due to barrier mitigation for each subnetwork is determined by equation (3.16). It should be noted that the R-FPBRP(S) is a linear rescaling of the R-FPBRP model. The implication of this is that the the relationship between fish species richness and connectivity is assumed to be linear. This is necessary in order to maintain an MILP structure. Ecological intuition suggests that as average connectivity between river subnetworks approaches unity, fish species responses are unlikely to remain linear. Consequently, the R-FPBRP(S) may be best employed in river systems suffering moderate to high levels of fragmentation, for which moderate levels of investment in river barrier mitigation are being considered. Should the analysts wish to specify a non-linear relationship between connectivity and species richness, it would be necessary to employ heuristics or linearize the relationship in some manner. The potential to develop these types of approaches is discussed further in Chapter 6.

3.4. River Wey Case Study

3.4.1. Background

The River Wey is a tributary to the River Thames and is located in the South East of England and covers an area of approximately 900 km^2, as shown in Figure 3.2. The River Wey comprises of two branches, which meet approximately 15 km to the west of Guildford, and flows into the non-tidal River Thames at Weybridge. There are three operational canal systems within the catchment, comprising: the Wey Navigation (between Guildford and Weybridge), the Godalming Navigation (heading west from Guildford) and Basingstoke Canal (heading west from Weybridge). Agriculture is the principal land-use in the south and west of the catchment, however, the north of the catchment is primarily urban (EA, 2008).

In England the Environment Agency is the public body responsible for managing water resources and their fisheries. The EA's Fisheries Action Plan for the Wey valley identified the presence of physical obstructions as a key pressure on the fish diversity and abundance in the catchment (EA, 2009). In order to help assess this problem in a systematic way the International Centre for Ecohydraulics at the University of Southampton have prepared an inventory of these obstructions within the main reaches of the River Wey catchment. In total, 805 barrier structures were identified, which include weirs, dams, sluices, culverts, locks, fords, bridge aprons, mills and cascades. The location of each barrier was subsequently matched to the EA's detailed river network (DRN) using GIS techniques.

In order to rationalize the river network for the River Wey catchment, all watercourses identified as a drain on the DRN were removed given their low ecological value.[1] Furthermore, where man-made channels introduced braids into the system, they were terminated immediately before rejoining the natural river channel in order to maintain a dendritic structure. Following these adjustments, the final dataset employed in the analysis comprised 1,160km of watercourses with 670 different barriers, as shown in Figure 3.2.

The upstream and downstream passabilities of a subset of 129 of these barriers were determined by the University of Southampton using rapid assessment protocols (based on Kemp et al. (2008)). For the purposes of the analysis presented here passabilities for adult trout were adopted. For barriers whose passabilities were not specifically determined, these have been inferred from similar barriers assessed

[1] Drains comprise of watercourses identified as ditches, reens, rhynes or drains as identified on Ordnance Survey mapping or by local Environment Agency staff.

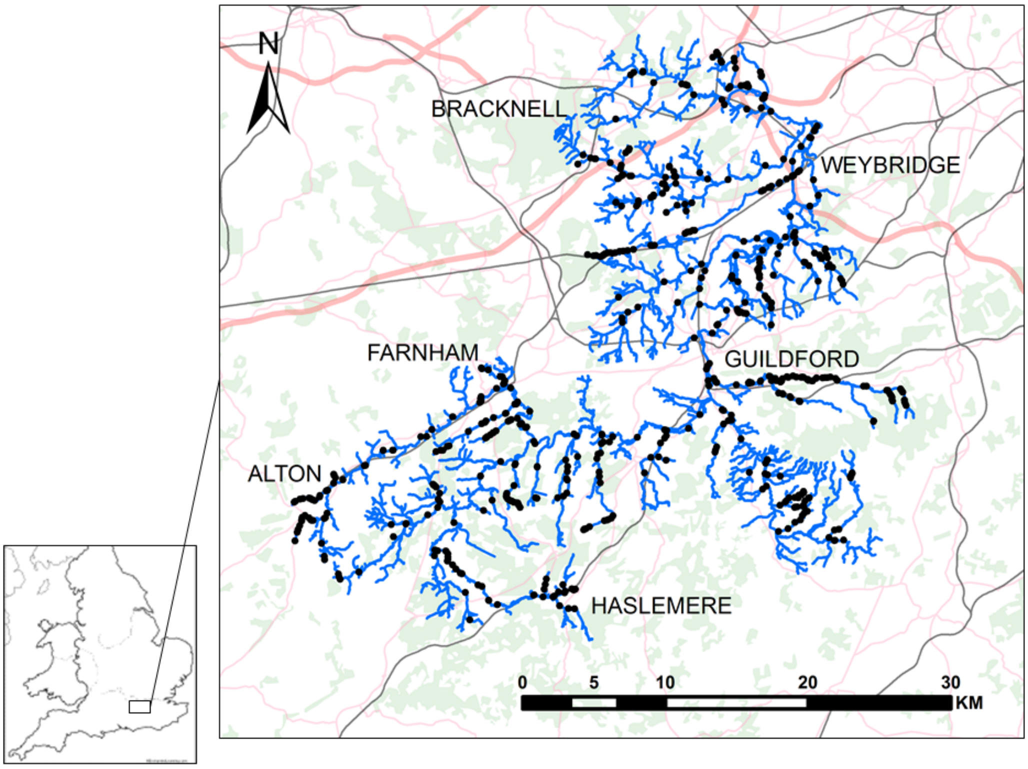


Figure 3.2.: Location and extent of River Wey catchment. Barriers are represented by small black colored dots.

elsewhere in the catchment. The amount of habitat above any given barrier was characterized as the summed river length between that barrier and its immediate upstream barriers or the terminal points of the river network. Only a single habitat type was considered for the catchment as over 75% of river stretches in the DRN are classified as primary river. The dispersal distance for fish (d') was assumed to be 12.5km (based on a sensitivity analysis of results from the model specified in Section 3.4.3).

Overall 650 out of the 670 barriers were considered candidates for mitigation action, for each of these a single mitigation project was considered. Barriers outside the middle and lower reaches of the main river stem and navigation sections were considered suitable candidates for complete removal, thereby restoring full passability in both directions (i.e., $p_j^0 + p_{ij} = 1.0$). Barriers associated with the middle and lower reaches of the main river stem were not considered suitable for removal due to the adverse effect on navigation in this part of the river system. These barriers were considered candidates for the provision of fish passes. Fish passes were assumed to increase upstream passability to 0.75 and restored full passability in the downstream direction ($p_j^0 + p_{ij} = 0.75$), generally reflecting the findings of Noonan et al. (2012). For the purposes of the analysis, it was assumed that bidirectional passability at locks could be increased to 0.65 via investment in more regular improved operations. The costs of barrier mitigation were estimated on the basis of costs provided by the River Restoration Council (pers. coms.) for work at similar structures and from information published by the EA (EA, 2010). Based on these costs, the cost of mitigating all 650 candidate barriers within the River Wey is estimated to be £53,355,000 or approximately £55 million.

3.4.2. Fish Survey Dataset

The Environment Agency completed 145 fish surveys within the River Wey catchment between October 1989 and October 2011 as part of ongoing monitoring. The surveys were completed using electrofishing methods. The average length and area of river surveyed was approximately 120m and 1,000m^2, respectively. In total, these surveys identified 22 different species, with an average of approximately 6 different species and 96 individual fish identified during each survey event.

All survey observations where no fish species diversity was encountered (i.e., zero or only a single species recorded) were removed from the fish survey dataset on the basis that such observations were indicative of highly localized pressures (e.g., pollution) or sampling error. In addition, all observations outside of the 2002 to 2011 period (i.e., those from 1989, 1990 and 1991) were excluded in order to maintain a contemporary monitoring period. This resulted in a final dataset of 121 observations to investigate the significance of subnetwork connectivity on species richness in the River Wey.

3.4.3. Statistical Analysis of Fish Survey Data

In order to parametrize the R-FPBRP(S) model, it is necessary to estimate the magnitude and confirm the significance of the effect of subnetwork connectivity on species richness. In the analysis that follows, the significance of the C metric with respect to the fish species richness determined during survey events completed in subnetworks of the River Wey is investigated. The *a proiri* expectation is that fish species richness is influenced by both the subnetwork connectivity and its associated stream size (represented by the square root of the total length of upstream habitat, $\sqrt{USL_j}$). Dummy variables for time are also included in the estimation procedure to control for temporal variation across survey years and increase the accuracy of the parameter estimates. Consequently, the statistical model for the River Wey takes the following form:

$$R_j = \beta_0 + \beta_1 C_j^0 + \beta_2 \sqrt{USL_j} + \sum_{t=1}^{T} \beta_{2+t} dummy_t + \mu \tag{3.17}$$

where variable R_j is the species count observed during a survey event, C_j^0 is the current C metric value for the subnetwork in which the survey event occurred, β_0

is a constant, $dummy_t$, $t = 1 \ldots T$, are a series of dummy variables for the year the fish surveys were undertaken with associated parameters β_{2+t} and μ is an error term. Given the dependent variable R_j is characterized as a non-negative integer, ordinary least squares (OLS) regression is not technically appropriate given the discrete nature of the data and the fact they are not normally distributed. The use of a Poisson regression model is an alternative approach commonly employed in order to analyze count data. A good summary of the model is provided by Green (2008). Essentially, the model specifies that each dependent variable observation (y_i) is drawn from a Poisson distribution that is characterized solely by its mean (λ_i). The expected value of y_i ($E(y_i)$) and its variance ($Var\ (y_i)$) both equal λ_i. The parameter λ_i varies across individuals conditional on a vector of dependent variables ($\mathbf{X}_i$), such that $\lambda_i = E(y_i|\mathbf{X}_i) = \exp\left(\boldsymbol{\beta}'\mathbf{X}_i\right)$. Specifying the log-linear relationship $\ln \lambda_i = \mathbf{X}_i\beta$ allows the values of β to be obtained via maximum likelihood estimation. In order to avoid the restriction of equal mean and variance (equidispersion), the generalized Poisson modeling approach proposed by Consul and Jain (1973) is employed. This generalized Poisson model relaxes the assumption of equidispersion by allowing the variance for the distribution of the dependent variable ($Var\ (y_i)$) to be characterized as a function of λ_i and an associated scaling factor (θ), such that $Var\ (y_i) = \lambda_i \left(1 + \theta\lambda_i\right)^2$. A negative value for θ implies underdispersion of the data, a positive value overdispersion. A value of zero implies that the classical Poisson model applies (i.e., $E(y_i) = Var\ (y_i) = \lambda_i$).

3.4.4. Statistical Analysis Results

The statistical model specified in equation (3.17) was estimated using the LIMDEP version 10 software package (Econometric Software, 2012). The results are summarized in Table 3.3. The dummy variables for survey years are omitted from the table as their inclusion was purely to control for temporal variation. A conventional OLS regression reveals that approximately half the variation observed in fish species richness R is explained by the model ($R^2 = 0.47$) and that the key explanatory variables are significant at the 1% level. For the preferred generalized Poisson regression, the scale parameter θ is negative and significant at the 1% level, confirming underdispersion of the data. The likelihood ratio test confirmed that the key variables are jointly significant at the 1% level. The coefficient estimate for C is significant at the 5% level. This parameter is not directly comparable to the OLS coefficient but represents the effect on $\ln R$ of a one unit increase in C. A comparable partial effect can be calculated for C and $\sqrt{USL}$ by evaluating the effect of these variables on the expected value of R when computed at the means of the sample data. These results are reported in the final ($^{dy}/_{dx}$) column in Table 3.3. The direct marginal effect for $\sqrt{USL}$ remains significant at the 1% level and appears reasonably robust when switching from the OLS to the generalized Poisson regression model. The marginal effect of 15.43 for C is significant at the 95% confidence level. Given this reflects the linear relationship between R and C, this is the value the parameter estimate

β_1 takes in the objective (3.15) of the R-FPBRP(S) model.

Table 3.3.: Results of fish species richness statistical analysis for the River Wey dataset.

	OLS	Generalized Poisson	
	Coeff (s.e.)	Coeff (s.e.)	dy/dx (s.e.)
β_0	4.35 (0.89)***	1.54 (0.12)***	-
C	20.79 (7.86)***	2.40 (1.14)**	15.43 (7.27)**
$\sqrt{USL}$	0.0052 (0.0006)***	0.0007 (0.0001)***	0.0047 (0.0006)***
	Model Parameters (s.e.)		
θ	-	-0.044 (0.008)***	
R^2	0.47	-	
$pseudo - R^2$	-	0.042	
AIC	509.2	520.9	

*** Significant at 1% level, **Significant at 5% level.

It is noted that the parameter estimate for C (15.43) is relatively high given only 22 fish species have been identified in the catchment. This may reflect the high degree of fragmentation in the River Wey system. It is also noted that due to the high degree of fragmentation within the system and the limited number of subnetworks for which fish survey observations are available, the maximum connectivity value within the input data is only 0.098. Consequently, the absolute error associated with predicted fish species richness responses to improved connectivity (*ceteris paribus*) is likely to increase substantially as connectivity tends to unity. In any practical application, this situation would be addressed by undertaking a targeted sample to support the analysis, rather than relying on the existing convenience sample.

3.4.5. Optimization Model Results

The R-FPBRP and R-FPBRP(S) models were coded in OPL using CPLEX studio version 12.5. CPLEX is a state-of-art commercial software package that employs a branch-and-bound algorithm combined with cutting planes to solve MILPs such as R-FPBRP and R-FPBRP(S). All experiments were run on the same dual-core Toshiba Satellite Pro R850-15F laptop (Intel i3 processor, 2.10 GHz per chip) with 8GB of RAM. The performance of the CPLEX implementation of the R-FPBRP and R-FPBRP(S) models on the River Wey dataset is presented in Table 3.4. In addition, Table 3.4 also reports the performance of the linear reformulation of the R-FPBRP model presented by O'Hanley et al. (2013b). The "Objective" of R-FPBRP in Table 3.4 gives the maximum connectivity weighted habitat for a given budget amount. The time to generate an optimal or best feasible solution is measured in

CPU hours, minutes and seconds. The "% Gap" column is the percentage difference between the best feasible solution generated by the original O'Hanley et al. (2013b) linear reformulation of the R-FPBRP within 12 hours of CPU time and the optimal solution. The R-FPBRP(S) "Objective" reports the maximum average net species gain for subnetworks across the catchment. In cases where this model is unable to generate a verified optimal solution within 12 hours of CPU time, the percentage gap (% Gap) between the optimal solution and best feasible solution found is reported. The current amount of accessibility weighted habitat in the River Wey (i.e., given a zero budget) is 67km.

Table 3.4.: Performance of the R-FPBRP and R-FPBRP(S) models on the River Wey dataset.

Budget	R-FPBRP Model				R-FPBRP(S) Model	
	Objective	Time (hh:mm:ss)		%	Objective	Time
(£M)	(km)	Prob. Chain*	Linear**	Gap	(Species Gain)	(hh:mm:ss)
2.5	171.84	02:03:54	04:32:56	-	1.395	03:20:19
5.0	241.33	10:19:14	-	0.037	2.319	08:01:38
10.0	411.75	10:33:09	11:48:27	-	4.586	07:14:51
15.0	606.57	06:21:53	10:52:35	-	7.177	06:03:15
20.0	743,82	09:39:27	-	0.005	9.003	07:13:19
25.0	858.73	04:21:00	-	0.117	10.531	06:17:25
30.0	954.05	05:24:29	-	0.081	11.799	05:37:11
35.0	1,026.71	02:38:28	-	5.201	12.765	02:09:33
40.0	1,082.10	04:13:14	-	5.742	13.502	03:55:20
45.0	1,122.86	03:50:29	-	5.591	14.044	05:37:26
50.0	1,152.01	01:51:09	-	0.001	14.432	02:27:01
55.0	1,160.11	00:01:31	00:02:57	-	14.539	00:02:05

*Prob. Chain refers to the R-FPBRP formulation presented in Section 3.3.3.
**Linear refers to the R-FPBRP model presented in O'Hanley et al. (2013b).

The first observation that can be made with respect to Table 3.4 is the amount of time required to generate an optimal solution using either the R-FPBRP or R-FPBRP(S) formulations is generally quite long (up to approximately 10.5 hours for the £10M budget using the R-FPBRP model). This reflects the highly complex nature of the case study area, which comprises of 670 barrier subnetworks. Therefore, there is a total of 223,446 possible inter-barrier and 670 intra-barrier routes. This results in 224,116 z variables, 223,446 y variables and a total of 1,119,240 constraints associated with these variables at any given budget. Table 3.4 clearly demonstrates the significantly increased efficiency of the probability chain based approach to evaluating cumulative passability terms by providing optimal solutions in several hours less than the original O'Hanley et al. (2013b) linear reformulation. Moreover, for 8 out of the 12 budget levels, the original linear reformulation could not generate an optimal solution within 12 hours of CPU time. At budget levels of £35M, £40M and

£50M, the optimality gap exceeded 5% (roughly equivalent to 58km of accessible habitat).

A second interesting observation that can be made regarding Table 3.4 is an overall pattern of diminishing marginal improvements in accessible habitat / species richness delivered with increasing budget. However, below a budget of £15M, a pattern of reasonably steady returns to investment is observed. Above this, diminishing marginal returns are observed, becoming pronounced for the R-FPBRP(S) model above a moderate budget of £25M. This is clearly illustrated in Figure 3.3.[2] The pattern of decreasing returns with investment has been observed in a number of studies employing optimization modeling frameworks to inform barrier mitigation planning (e.g., Kuby et al., 2005; O'Hanley and Tomberlin, 2005; Zheng et al., 2009; O'Hanley, 2011). The results shown in Figure 3.3 may best be employed to identify upper bounds for investment reflecting where the best bang-for-the-buck can be achieved.[3] For example, a review of Figure 3.3 suggests that investments substantially above £25M (yielding approximately 10 additional species) may not be warranted given that around 70% of the potential ecological improvement (10 additional species out of a possible 14) has been achieved.

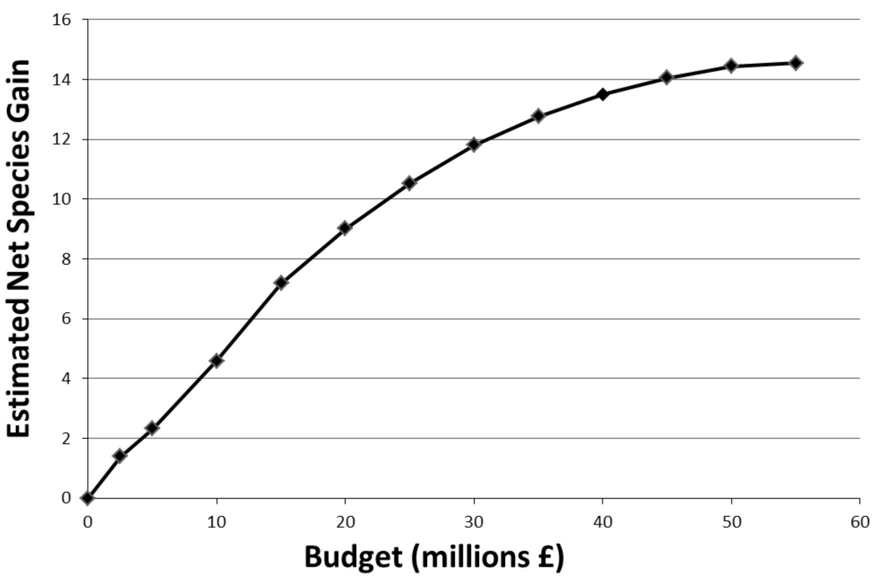


Figure 3.3.: Maximum species richness gain versus budget for the River Wey dataset..

Table 3.5 summarizes the characteristics of the barriers that are selected for mit-

[2]Given that the R-FPBRP(S) model is essentially a linear rescaling of the R-FPBRP a graph of maximum accessible habitat versus budget would have the same shape as the graph in Figure 3.3 (along with a shift in the intercept term to reflect the current amount of accessible habitat).

[3]It should be noted that this curve is not continuous but comprises of a series of step-wise increments at fine scale. This implies thresholds for investment exist in which a sufficient budget is required to make further connectivity improvements.

igation action under the different budget solutions. The “All Barriers” column in Table 3.5 provides the breakdown, by type, of the 650 candidate barriers for mitigation in the River Wey system. The “Solution” columns show the percentage of each barrier type that is mitigated under the optimal solution for the stated budget level. “Others” comprise bridge aprons, fords, mills, dams, a man-made cascade and a constriction. “Main stem barriers” are those associated with the main stem of the River Wey and “Big barriers” are those on Primary river stretches with head differences ≥1m. Average values for selected properties of the respective sets of barriers is provided at the bottom of the table.

Table 3.5 reveals that weirs and culverts are the dominant barrier types in the system, comprising 257 and 268 out of the total 650 respectively. Table 3.5 also shows that culverts are generally not selected for mitigation at lower budget levels. For instance, only 10.4% of these structures are identified for mitigation action under the optimal solution for a £15M budget (beyond which diminishing returns on investment were observed). A similar situation is observed for screens, with only 13.3% of these structures identified for mitigation at a £15M budget level. For all the other barrier types between 28.8% (weirs) and 40.0% (others) are selected for mitigation action at this budget level. This suggests that despite their abundance within the system, culverts (and screens to a lesser degree) are not the significant drivers of overall connectivity issues within the River Wey catchment. This observation is not surprising, culverts and screens are typically associated with smaller river reaches towards the extremities of the system, consequently they will obstruct a smaller number of routes than barriers in higher Strahler order reaches. Indeed, it is expected the optimization model will target barriers in main stem and its direct tributaries, through which a high proportion of subnetwork to subnetwork routes will pass.

Table 3.5 shows that barriers associated with these parts of the river are indeed targeted for action a lower budget amounts, for example 100% of “Main stem barriers” and 62.7% of “Big barriers” (barriers in primary river stretches with head differences ≥ 1m) are selected for mitigation at the £15M budget level. These barriers in the larger reaches of the river system will retain a greater volume of water, as such they will be more substantial and expensive to mitigate. Table 3.5 reveals this to be the case, with increases in the average total length of upstream habitat retained USL and mitigation costs observed for the barriers selected up to £15M solution. At budget levels above £15M steadily decreasing values for these characteristics with budget are observed. Table 3.5 also reveals lower average passability values for the barriers selected for mitigation at low to moderate budget levels (i.e., up to £20M). This is considered to be indicative of the larger, low passability, barriers in the larger lower reaches of the river system being prioritized for mitigation. A final observation that can be made with respect to Table 3.5 is that at low budget levels the optimization model targets barriers at the base of the large subnetworks. For example, the average subnetwork habitat length v above barriers selected for mitigation at the £5M budget is 7.834km and diminishing decreases in these values

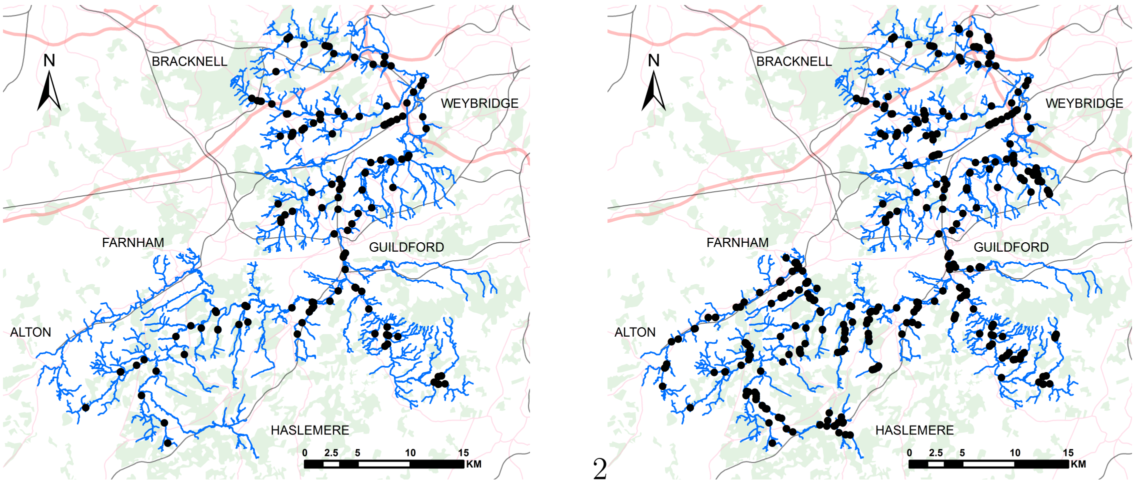
Table 3.5.: Analysis of river barrier mitigation solutions for the River Wey dataset.

	All	Solution (budget £M)									
	Barriers	5	10	15	20	25	30	35	40	45	50
Barrier types											
Culverts	268	3.4%	10.1%	10.4%	19.0%	26.5%	38.1%	55.2%	70.1%	74.6%	87.3%
Weirs	257	13.2%	19.8%	28.8%	39.7%	48.6%	53.3%	59.9%	67.3%	82.5%	93.4%
Sluices	41	9.8%	17.1%	36.6%	46.3%	61.0%	75.6%	75.6%	78.0%	87.8%	92.7%
Locks	34	0.0%	29.4%	29.4%	32.4%	47.1%	47.1%	58.8%	61.8%	70.6%	97.1%
Screens	30	3.3%	13.3%	13.3%	20.0%	23.3%	33.3%	46.7%	60.0%	73.3%	96.7%
Others	20	20.0%	40.0%	40.0%	45.0%	50.0%	70.0%	75.0%	80.0%	80.0%	90.0%
Total	650	8.0%	16.5%	21.4%	30.5%	39.1%	47.7%	58.8%	68.9%	78.5%	91.1%
Main stem barriers	27	14.8%	33.3%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Big barriers	67	14.9%	28.4%	62.7%	70.1%	80.6%	89.6%	89.6%	92.5%	100.0%	100.0%
Average											
p^0	0.12	0.06	0.10	0.08	0.09	0.09	0.10	0.11	0.12	0.11	0.11
cost (£)	82,085	96,154	93,439	107,892	101,010	98,421	96,768	91,623	89,286	88,218	84,454
v (km)	1.693	7.834	5.719	5.189	4.154	3.581	3.145	2.668	2.347	2.112	1.851
USL (km)	38.569	63.442	101.003	145.833	108.966	88.471	75.798	62.229	53.876	48.856	42.321

p^0 is initial bidirectional passability of a barrier, cost is cost of mitigating a barrier, v is the length of habitat within the subnetwork that the barrier retains, USL is the total length of river above a barrier to the limits of the system.

are observed with increasing budget. This suggests that at very low budget amounts (e.g., $<$ £10M) an appropriate heuristic may be to sequentially mitigate the barrier obstructing direct access between the two largest adjacent subnetworks in the River Wey system until the budget is expended.

As a final piece of analysis the spatial distribution of barriers targeted for mitigation at the £15M and £30M budget levels are contrasted in Figure 3.4.



(a) (b)

Figure 3.4.: Comparison between spatial distribution of barriers targeted for mitigation at £15M budget (a) and £30M budget (b). The barriers targeted for action are represented by the black dots.

As expected, Figure 3.4a reveals that at the lower budget level the barriers selected for mitigation are often associated with the main stem of the River Wey. Figure 3.4a also reveals that at the lower budget level barriers in tributaries to the main river stem that exhibit limited bifurcation (e.g., the Tillingbourne to the east of Guildford and the northern branch of the River Wey through Alton and Farnham) are not targeted for mitigation action. Whereas, barriers in areas with high degrees of bifurcation, notably near the mouth at Weybridge where several tributaries converge, are targeted for action. This, again, reflects that the optimization model will target barriers through which a high proportion of subnetwork to subnetwork routes will pass. Furthermore, in areas of dense bifurcation the benefit of improving connectivity between these subnetworks will be less affected by the inverse distance weighting term in the C metric.

The general picture that emerges is it appears to be the larger, low passability barriers that are generally more expensive to mitigate and also obstruct passage through the main river stem, higher Strahler order reaches or exist in areas of dense river branching that are prioritized for action in the River Wey system. For the

River Wey system culverts and screens are not typically identified as being these types of barriers.

It is stressed that the R-FPBRP(S) analysis presented for the River Wey is meant for illustrative purposes only. Significant uncertainty exists with respect to the species-connectivity response parameter (β_1 in equation (3.15)) given the use of a convenience sample of fish survey data rather than one specifically designed to support the analysis. Furthermore, only approaching 20% of the barriers in the analysis have been specifically assessed for passability. In any real application the quality of the optimization model solutions would be much improved with the provision of a more comprehensive inventory of barrier passability.

3.5. Conclusions

The presence of river barrier infrastructure across the world has substantially reduced the longitudinal connectivity of fluvial ecosystems. The negative impacts that artificial barriers have on fish populations are well-known. There is now increasing interest amongst ecologists, river managers and policy makers in the removal or mitigation of these barriers in order to improve connectivity and, therefore, the ecological integrity of river environments. This chapter presents a toolkit for the cost-effective prioritization of barrier mitigation actions in order to improve connectivity for resident fish species.

The optimization models presented contribute to the limited literature on optimization frameworks designed to improve longitudinal connectivity at the catchment scale. Specifically, a new linear formulation for the Resident - Fish Passage Barrier Removal Problem (R-FPBRP) is proposed, which employs probability chains to evaluate cumulative passability. This results in a more efficient and scalable model that can be readily implemented using off-the-shelf optimization software. An extension of this model (R-FPBRP(S)) is also presented that can be used in conjunction with standard statistical approaches to maximize average gains in species richness across a catchment.

The scalability of the R-FPBRP and R-FPBRP(S) models is demonstrated using a dataset of 670 barriers from the River Wey in the UK. Whilst the models took up to 10.5 hours to solve, this reflects the complexity of the given case study. The greater efficiency and scalability of the new R-FPBRP formulation is demonstrated through a comparison with the original O'Hanley et al. (2013b) linear formulation. The original formulation is found to be unable to provide optimal solutions within 12 hours of computing time for the majority of the experimental budget values. The probability chain approach, in contrast, is able to generate optimal solutions within 11 hours and typically less than 7 hours of computing time for all budget levels. For the River Wey system, investment in river barrier mitigation substantially above £25M may not be economically rational given the diminishing marginal returns observed beyond this point and that approximately 70% of the potential improvement is obtained at this budget level. The analysis of barriers that are selected for mitigation action under different budget scenarios indicates that it is the larger, low passability barriers with higher mitigation costs, which generally occur in the main river stem, higher Strahler order reaches or areas of dense river branching that are prioritized for action in the River Wey system. These barriers tend to be weirs, sluices or locks, rather than culverts or screens.

The methods presented here are believed to be of direct use to decision makers involved in river ecosystem management. The optimization models presented readily generate prescriptive solutions for barrier mitigation action that maximizes restoration gains given available resources. These solutions can, in turn, be implemented *in toto* or form the basis for more detailed modeling and fine-tuning latter on. This is a distinct advantage compared to other river barrier prioritization methods, such as scoring and ranking or graph theoretic approaches, which are either inefficient or merely descriptive (i.e., they model solutions proposed by an analyst rather than providing a recommended best course of action). The optimization models can also be used to produce Pareto-optimal trade-off curves, such as in Figure 3.3, to reveal how environmental improvements vary with different levels of investment. The economic value of benefits associated with improving the biophysical attributes of river ecosystems (i.e., average fish species richness) can also be estimated using established non-market valuation techniques (e.g., Morrison and Bennett (2004); MacDonald et al. (2011)). Consequently, the methodology underlying the R-FPBRP(S) model readily lends itself to a bio-economic framework that can estimate the social benefit value of environmental improvements delivered by barrier mitigation action. Given the increasing use of cost benefit analysis in environmental decision making, this is anticipated to be of use to government agencies involved in river management and policy. Research in this regard is presented in Chapter 5.

4. The Significance of Socioeconomic Variation in Benefits Transfer: An Investigation in the Context of Fish Passage Improvement

4.1. Abstract

River barriers, such as dams, weirs and culverts, disrupt river habitat connectivity, causing adverse impacts on fish and other species. This compromises the ability of river ecosystems to provide services that contribute to human well-being. This chapter presents the findings of choice experiments (CEs) investigating preferences for improvements in ecosystem services arising from increases in fish species richness and abundance following river barrier mitigation. A CE considering a generic local river is initially administered to a national sample. The same CE but considering the River Wey in South East England is then administered to a local sample. In both CEs, significant positive preferences for the outcomes of river barrier mitigation are found. Respondents to the River Wey survey were willing to pay more for river improvement for reasons other than the improvements in attributes offered. This may reflect local stewardship motivations that emerge once the river's anonymity is broken. These motivations are envisaged to vary across catchments, implying benefit transfers that incorporate unobserved welfare benefits are likely to suffer error in the context of fish passage improvements. Socioeconomic variables did not successfully explain the differences in preferences across and between benefiting populations. This indicates that these types of variables cannot be used to correct benefits transfer error in the context of fish passage improvement. Environmental attitude was found to be a more consistent predictor of attribute preferences in the CEs. However, as preferences to increase fish species richness are found to be essentially homogenous, the implicit prices (IPs) for this attribute maybe suitable for direct transfer. Equivalence testing confirmed a generic IP for fish species richness estimated from the national CE was robust for transfer to the local River Wey case study. A similar generic IP for fish abundance is found to be less robust but potentially useful to decision makers. This is believed to be due to the fish abundance

attribute being associated with community benefits that are more susceptible to population effects.

4.2. Introduction

River systems comprise the most complex, dynamic and bio-diverse ecosystems on earth. They also play an essential role in the transport of organisms and matter through the landscape (Dynesius and Nilsson, 1994). However, human societies have extensively modified fluvial ecosystems across the globe in order to provide socio-economic benefits such as water supply, flood suppression, power and transportation. Obtaining these benefits typically involves the construction of river infrastructure that fragments the continuity of rivers and substantially alters their natural flow, thus transforming the biological, morphological and physio-chemical characteristics of rivers and their ecosystems (Bednarek, 2001). The presence of these physical obstructions restricts or eliminates the ability of fish and other aquatic species to reach essential breeding and rearing grounds (Stanford et al., 1996). Numerous studies have demonstrated the negative effects of these artificial river barriers on migratory and resident fish populations (Fullerton et al., 2010; Sheer and Steel, 2006; Catalano et al., 2007; Nislow et al., 2011).

Removing barriers to fish passage has been demonstrated to deliver increased spawning (Burdick and Hightower, 2006), fish density (Gardner et al., 2013), diversity (Catalano et al., 2007) and rapid colonization of formerly impounded, upstream reaches (Roni et al., 2008). As such there is now considerable interest in river barrier removal or mitigation as a cost-effective means of improving fish populations at the watershed scale (Roni et al., 2002).

Increasingly, the drivers for river ecosystem improvements are legislative, such as the Endangered Species Act in the US and the Water Framework Directive (WFD) in the EU. Across England and Wales, the Environment Agency (EA) has prioritized 2,500 river barriers for mitigation action in order to meet WFD and Eel regulation requirements at an estimated cost of £540M (Kemp and O'Hanley, 2010). Analysis of the costs and benefits of such expenditures are routinely carried by government agencies when considering implementing policies, such as river barrier mitigation. Indeed the WFD specifically incorporates a requirement for estimating costs and benefits in catchment management plans (Hanley et al., 2006b; Del Saz-Salazar et al., 2009; Johnston and Rosenberger, 2010). Where costs are disproportionate to estimated benefits, derogation's from the requirements of the WFD may be sought (Hanley et al., 2006b). As the social benefits of river ecology improvements typically accrue outside of well-functioning markets, non-market valuation techniques are required in order to inform the cost benefits analysis (CBA) of river barrier mitigation action. However, undertaking repeated valuation studies across catchments is both expensive and time consuming and, therefore, likely to be limited to large controversial cases (Hanley et al., 2006b). Benefits transfer, the practice of transferring valuation estimates from one study site to another site, provides an inexpensive solution to this problem (Morrison and Bennett, 2004). Although the advantages of benefits transfer are obvious, there is a considerable debate within the literature regarding the validity and appropriate methodologies for this approach (Hanley et al., 2006).

In this chapter, the willingness-to-pay (WTP) for local river ecosystem improvements that could be delivered via river barrier mitigation actions is estimated using the choice experiment method. The choice experiment is administered to a nationally representative sample and to a locally targeted sample. In the subsequent analysis, the significance of socioeconomic, use, and environmental attitude variables on choice is investigated and the implications of the results with respect to population effects and benefits transfer error evaluated. In addition, the validity of applying the nationally derived estimates for river ecology improvements for a generic local river to a specific local river context is evaluated.

This study contributes to the literature by adding to the paucity of valuation studies on fish passage improvement at multiple river barriers. The use of well-grounded ecological indicators enhances the potential for the estimates presented to be transferable between catchments. The analysis presented materially contributes to the understanding on policy scenarios in which benefits transfer may be more appropriate and evaluates a novel form of benefit transfer using generic value estimates.

The structure of the chapter is as follows. In Section 4.3, the relevant choice experiment literature and the practice of benefits transfer is briefly reviewed. Section 4.4 introduces the case study river and details the development and implementation of the choice experiment survey instruments. Section 4.5 presents the results from the choice experiments. Section 4.6 covers the welfare and benefits transfer analysis. Concluding remarks are provided in Section 4.7.

4.3. Methodological Review

4.3.1. Choice Experiment Methodology

In a choice experiment (CE), respondents are asked to choose between different consumption bundles of environmental goods that are characterized by the levels of certain attributes the goods possess, one being a price for provision (Hanley et al., 1998b). As the technique is based upon hypothetical stated preferences for environmental goods, it is particularly suited for capturing non-use values (Adamowicz et al., 1998).

The technique is based upon Lancaster's characteristics theory of goods, with the associated choice models underpinned by random utility theory (Hanley et al., 1998b). Under the random utility framework, U is composed of a deterministic component

V (characterized by the levels of the k number of CE attributes) and a random unobservable component ε (Manski, 1977). In a CE, the probability a respondent chooses any given bundle i over all others offered $j \neq i$ from the set J of all choice alternatives is the probability that $U_i > U_{j \neq i}$ (Hanley et al., 1998b). Therefore, the probability a respondent prefers bundle i over all the other alternatives can be specified as the following multinomial logit (MNL)[1] or conditional logit (CL)[2] model, where μ is a scale parameter (typically assumed to equal 1):

$$P\left(U_i > U_{j \neq i}\right) = \frac{\exp\left(\mu V_i\right)}{\sum\limits_{j \neq i \in J} \exp\left(\mu V_j\right)} \qquad \forall\, i,\, j \in J \tag{4.1}$$

This logit specification in equation 4.1 can be estimated via a maximum likelihood function to yield parameter estimates for the various attributes within the deterministic component of the utility function (i.e., V) (Hanley et al., 2001). The marginal WTP or implicit price (IP) for a unit increase in the level of an attribute k is then given by:

$$WTP_k = \beta_k / \beta_c \tag{4.2}$$

where β_k is the estimated coefficient for attribute k and β_c is the estimated coefficient for the cost attribute c (the marginal utility of income that is constant for all attributes). It should be noted that as the MNL and CL models impose homogenous preferences across respondents and the independence of irrelevant alternatives (IIA) assumption. Consequently, its application is generally considered restrictive and inappropriate in the more recent literature, whereas models that cater for preference heterogeneity across respondents are preferred (e.g., Birol et al., 2009).

4.3.2. Random Parameters Logit Model

The random parameters logit (RPL) model is now commonly applied to account for heterogeneity across individual respondents in CE studies (e.g., Colombo et al. (2007); Johnston and Duke (2010); Zhao et al. (2013)). The model specification allows for the vector of parameter estimates in the utility function ($\boldsymbol{\beta}$) to vary across individuals, consequently these estimates become characterized as having a standard deviation that captures the individuals' preference heterogeneity. With this generalization the model does not impose the IIA assumption and its restriction on substitution patterns (Train, 1998). This differs from the more restrictive MNL and CL models, where all the behavioral information in β is assumed to be captured by its mean.

In the CE, the utility function for respondent q choosing over alternatives j ($j =$

[1] Only attributes are used as regressors (Mogas et al., 2006).

[2] Attributes and individuals' characteristics are used as regressors (Mogas et al., 2006).

$1 \ldots J$) takes the form:

$$U_{jq} = ASC_j + \sum_m \beta_m z_{qm} + \sum_k \beta_{qk} X_{kj} + \varepsilon_{jq} \tag{4.3}$$

where ASC_j is the alternative specific constant for bundle j, z_{qm} the value of the m^{th} observed value (e.g., socio-economic data) for respondent q and β_m the associated coefficient, X_{kj} is the k^{th} attribute value (including the cost) of bundle j and β_{qk} the associated marginal utility estimate specific to respondent q, finally ε_{jq} is the unobserved independent random term that is identically and independently Gumbel distributed across respondents. The variation in β for respondent q and attribute k is generated by the addition of a deviation parameter (η_{qk}). This represents the respondents' preferences relative to the average across the sample and provides the individual parameter estimate for each attribute (i.e., $\beta_{qk} = \beta_k + \eta_{qk}$). The model allows for η_{qk} to take on different distributional forms, reflecting the distribution of the associated parameter estimate (β_{qk}). The exact distributional form is specified by the analyst. The potential causes of respondent heterogeneity around β_k can further be investigated by specifying β_{qk} to also be conditioned by a vector of observed data for the respondent $\boldsymbol{z}_q$ (e.g., socioeconomic variables), such that $\beta_{qk} = \beta_k + \boldsymbol{\gamma}\mathbf{z}_q + \eta_{qk}$. Accordingly, the $\boldsymbol{\gamma}$ vector reveals the significance and magnitude of the effect of $\boldsymbol{z}_q$ on β_{qk}. The probability that any given respondent q chooses option i in the choice task (P_{iq}) is then given by:

$$P_{iq} = \int_{\boldsymbol{\beta}_q} L_{iq}\left(\boldsymbol{\beta}_q\right) f\left(\boldsymbol{\eta}_q \mid \boldsymbol{z}_q\right) d\boldsymbol{\eta}_q \tag{4.4}$$

where $L_{iq}\left(\boldsymbol{\beta}_q\right)$ is the logit probability associated with option i evaluated over the range of $\boldsymbol{\beta}_q$ values that emerge from the random variation induced by $\boldsymbol{\eta}_q$. The joint density of the k vector of random components $\boldsymbol{\eta}_q$ is given by $f\left(\boldsymbol{\eta}_q \mid \boldsymbol{z}_q\right)$. Where $f\,(.)$ is the joint density function associated with the distributions specified for $\boldsymbol{\eta}_q$. The model specified in equation (4.4) is often referred to as a mixed logit because the choice probability is a mixture of logit probabilities over the distribution of $\boldsymbol{\beta}_q$'s with a mixing distribution of $f\,(.)$ (Train, 2003; MacFadden and Train, 2000). As the above integral equation has no closed form, it must be approximated through simulation by repeatedly drawing values of β_{qk} from its specified distribution. This provides posterior densities for the values of $\boldsymbol{\beta}_q$ across all individuals and simulations undertaken. From these average values for the marginal utilities in equation (4.3) can be calculated. Parameter estimates are then obtained by maximizing the simulated likelihood function across the entire sample of respondents. An excellent discussion of the model is provided by Hensher et al. (2005).

4.3.3. Generalized Multinomial Logit Model

More general models that allow heterogeneity across individuals with respect to the scale of unobserved influences on choice (i.e., other than the improvements in attributes offered in the CE) have more recently been proposed in the choice experiment literature. Fiebig et al. (2010) describe a generalized multinomial logit II (G-MNL-II) Model that accounts for both individual heterogeneity with respect to attribute taste and the scale of the unobserved influences on their choice. Essentially, the G-MNL-II Model extends the RPL model by specifying that the vector of individual parameter estimates for attributes are further conditioned on a universal (i.e., across all attributes) individual specific scale factor σ_q,[3] such that $\beta_{qk} = \sigma_q \left(\beta_k + \eta_{qk}\right)$. Where σ_q itself is conditioned by a global scale parameter τ , a deviation term drawn from a normal distribution ε_{0q} and may also be conditioned on a vector of observed data for the respondent $\boldsymbol{z}_q$. As σ_q is positive, the following exponential specification is used:

$$\sigma_q = \exp\left(-\tau^2/2 + \boldsymbol{\theta}\boldsymbol{z}_q + \tau\varepsilon_{0q}\right) \quad where\ \varepsilon_{0q} \sim N\left(0, 1\right) \tag{4.5}$$

where, $\boldsymbol{\theta}$ reveals the significance and magnitude of the effect of $\boldsymbol{z}_q$ on σ_q.

4.3.4. Choice Experiment in Aquatic Ecosystem Valuation

CE has proven particularly effective in assessing the multi-dimensional nature of benefits provided via hydrological ecosystem improvements (e.g., Barkmann et al., 2008; Zander and Straton, 2010). However, CE studies focusing purely on ecosystem service benefits resulting from river barrier mitigation are rare in the literature. Johnston et al. (2011) present a CE applied to migratory fish passage restoration in the Pawtuxet watershed, Rhode Island, U.S.A. following the provision of fish passage facilities at 22 dams. They identify significant marginal WTP estimates for a 1% increase in resulting biological integrity ($1.19) and acres of habitat made accessible to migratory fish species ($1.09), with more modest, yet significant, estimates for increases in fish dependent wildlife ($0.64) and viability of migratory fish runs ($0.41). Interestingly, WTP for increases in catchable fish was not found to be significant, suggesting the primary motivations for the WTP estimates observed are non-use in nature. However, this observation is naturally influenced by the sampling frame and context of the watershed and the associated CE. For instance, Laitila and Paulrus (2008) demonstrate a significant WTP (approx. £7 - £12) for recreational fishing improvements following river barrier removal when targeting anglers using the Ljungan River in Sweden.

There exists an expanding body of CE studies examining the benefits of improvements to rivers realized through the Water Framework Directive (WFD). Hanley

[3] Here σ_q is the individual specific standard deviation of the idiosyncratic error term with respect to β_q that captures the variance in τ across the sample.

et al. (2006) estimate the benefits of delivering Good Ecological Status (GES) to UK water bodies under the WFD. They use three indicators of GES that the general public perceive of importance and are believed consistent with scientific interpretation, namely: ecology (range of fish, water plants, insects and birds), aesthetics (absence of sewage and litter) and river bank condition (vegetation and erosion) characterized by 'fair' and 'good' qualitative levels of improvement. For the River Clyde, CE estimated household marginal WTP for improvements in ecology and banksides to be around £40 and aesthetics approximately £30. For the River Wear, CE estimates for the marginal value of all three attributes are between £12 and £13. In a separate study, Hanley et al. (2006b) estimate WTP for reducing agricultural pollution and irrigation abstraction at two rivers in Scotland in the context of the WFD. They find marginal WTP for associated qualitative ecological improvements of £8.97 and £36.13, respectively, per household. NERA (2007) also undertook a substantial body of work to estimate the value placed by UK households on improvements in the water environment brought about by the WFD. Their study estimates that households marginal WTP to increase local waters to high quality is £0.88 / yr / % (catchment) and national waters £1.15 / yr / %.

More generally, Morrison and Bennett (2004) present a valuation of rivers in New South Wales, Australia. They find significant positive WTP amongst respondents for increases of 1 fish species (AUD $2.02 to $6.27). In a similar CE conducted in Victoria, Australia, Bennett et al. (2008) identify significant WTP amongst respondents for increases in fish (AUD $5.34 per %), vegetation (AUD $5.56 per %) and birds (AUD $22.07 per species). MacDonald et al. (2011) undertook a CE to value improvements in water quality and flow in the River Murray, Australia, finding significant WTP for fish species increases (AUD $1.71 to 3.58 per 1% increase / year).

In summary, this brief review confirms that respondents are likely to respond with significant WTP estimates for well-grounded ecological outcomes associated with river barrier mitigation (e.g., increases in fish species richness and total abundance) and that UK respondents have positive WTP for general improvements in aquatic ecosystem condition.

4.3.5. Benefits Transfer

In practice, benefits transfer involves calculating compensation surplus or WTP values for an environmental change at a policy site using the data collected at a similar study site (Colombo and Hanley, 2008). Whilst original valuation studies remain the ideal option, the time and budget constraints associated with the policy process often dictate that benefits transfer is the only feasible option for cost benefit analysis (Johnston and Rosenberger, 2010). In broad terms, there are two approaches to benefits transfer, unit value or benefit function transfer (Colombo et al., 2007). Direct transfer of unit values, such as compensating surplus or WTP are only acceptable if the study and policy sites and their respective populations are identical

(Hanley et al., 1998a). In order to account for almost inevitable differences in these characteristics, adjusted values can be used, however, these require the identification of variables that successfully explain the variation in WTP (Hanley et al., 1998a). Under benefit function transfer, the entire valuation function (or choice equation) is transferred (i.e., the parameter estimates for the study site are applied to a vector of variables relating to the policy site (Colombo and Hanley, 2008)).

Choice experiments are identified as potentially being well-suited to benefits transfer, as they allow for differences in environmental quality / attributes between study and policy sites (Morrison et al., 2002). Consequently, the parameter estimates for environmental variables at the study site can be used in conjunction with a vector of similar environmental variables at the policy site. Naturally, the environmental commodity must remain consistent for such transfer to be valid between the two sites (Johnston and Rosenberger, 2010).

4.3.6. Benefit Transfer Studies with CEs

The general process of demonstrating benefit transfer validity between a study and transfer site is based on comparing differences that emerge when applying a transferred deterministic utility function from a CE conducted at another study site compared to that estimated from an original CE at a policy site. For transfer purposes, it is important to check if the Implicit Prices (IPs) and compensating surpluses associated with various policy packages are consistent. In this regard, Hanley et al. (2006b) generally find no significant differences in IPs for ecological improvements in their study of rivers in Scotland. Similarly, Morrison et al. (2002) find no statistical differences between IPs for environmental attributes in Australian wetlands. Colombo et al. (2007) also find IPs for environmental attributes associated with soil conservation across two watersheds in Spain are not subject to significant differences. More generally, Johnston (2007) finds IPs for environmental attributes associated with land development did not vary across different communities in Rhode Island and Jiang et al. (2005) find no significant differences in IPs for coastal land protection sites in the USA. Van Bueren and Bennett (2004) find less promising results. Whilst IPs to reduce environmental degradation in Australia nationally were consistent across different regional populations, IPs to reduce such degradation at the regional (state) scale varied significantly. They suggest the reason for this difference may be driven by varying environmental attitudes amongst the respective populations. Morrison & Bennett (2004) also find significant differences between IPs for river ecology (including number of fish species) when conducting CE at various sites in New South Wales, Australia.

Information about the magnitude of error likely to be experienced when using benefits transfer is provided by determining the percentage mean difference in the estimates of Compensating Surplus for a policy package (i.e., the WTP for increasing a number of environmental attributes by certain amounts simultaneously)(Morrison et al., 2002). This is likely to be the most important test for a policy analysis as they represent the valuation aspect of the CBA process (Hanley et al., 2006b). Hanley et al. (2006b) generally find compensating surplus estimates for ecological improvements under the WFD remain robust when transferred between rivers in Scotland. More generally, Johnston (2007) also generally finds an absence of significant differences in compensating surpluses for environmentally sensitive land-use policies across different (but admittedly similar) sites and communities in Rhode Island. Morrison et al. (2002) find statistically significant differences in compensating surplus across policy scenarios for wetland improvements driven by differences in alternative specific constants (ASCs) and water bird breeding. Colombo et al. (2007) find significant differences in compensating surpluses for soil conservation policies between two river catchments in Spain. Jiang et al. (2005), also find significant differences in compensating surplus for coast land preservation policies for CE studies conducted in Rhode Island and Massachusetts.

Overall, there has been some success in demonstrating the validity of transferring implicit price's generated from CE's between study and policy sites, including studies involving rivers. However, when considering welfare estimates associated with policy packages, the associated compensating surpluses are generally found to be less robust to transfer error.

4.3.7. Population Effects and Benefits Transfer Error

Johnston (2007) suggests a "similarity hypothesis" whereby benefit transfer between sites will be increasingly valid the more similar these sites are. This is a notion generally supported in the literature elsewhere (e.g., Colombo and Hanley, 2008). Such similarity is not limited to the framing context in which the CE is administered (which is largely controlled for in the studies cited above) but also includes differences in the benefiting populations.

In order to control for population effects when transferring benefit functions from a study site to a policy site, differences in populations are often accounted for by the inclusion of socioeconomic variables in the benefit function (e.g., Colombo and Hanley, 2008). However, as Johnston and Rosenberger (2010) observe, there is no reason to assume the effects of socioeconomic factors on respondents' choices and WTP will be consistent and systematic across populations, finding their inclusion can actually increase transfer error for a study on land preservation policies. Hanley et al. (2006b) also find that socioeconomic variables were not significant in explaining respondents' choices for river ecology improvements in two parallel CEs in river catchments in East Scotland. These studies suggest that socioeconomic variables may be poor predictors of preferences for environmental improvements and more sophisticated means of capturing environmental attitudes are required. Van Bueren and Bennett (2004) suggest that differences in environmental attitudes may explain the population effects they observe. In this regard, Jiang et al. (2005) develop a

17-item scale on coastal land management attitudes. Using principle components analysis (PCA), they generated coastal environmental and access attitudinal measures that consistently improved the performance of choice models for purchasing coastal land parcels for conservation.

The brief review of the CE benefits transfer literature above suggests socioeconomic variation may only partially or inconsistently explain how preferences vary across different benefiting population groups in a number of benefit transfer applications. This chapter explores this further by administering the same CE considering a generic local river to a national sample and a specifically identified river (River Wey, South East England) to a sample of local residents. The significance of socioeconomic, use, and environmental attitude variables as drivers of preference heterogeneity and their influence on respondents' choices for river ecology improvements from barrier mitigation action is then investigated. In addition, the impact of such heterogeneity in the context of population effects that could compromise the validity of transferring national generic value estimates for river ecology improvements to the case study river is evaluated.

4.4. River Wey Choice Experiment

4.4.1. Background

The River Wey is located in the South East of England and comprises of two main branches and includes the River Wey and Godalming Navigations and Basingstoke Canal. In total, there are approximately 190 miles of watercourse associated with the river system. The University of Southampton have prepared an inventory of barriers within catchment (e.g., weirs, culverts and sluices) and identified 814 such structures providing complete or partial obstructions to fish movement. The Environment Agency Fisheries Action Plan for the catchment identifies that one of the key pressures on fish diversity and abundance is the presence of these physical obstructions (EA, 2009). This compromises the river system as a resource for recreational angling. The fisheries action plan also identifies that iconic species such as Otter and Kingfisher are dependent on the existence of healthy fish populations. Consequently, improving fish species richness and total fish numbers via river barrier mitigation action will improve ecosystem service provision from both the fluvial and associated riparian ecosystems of the River Wey.

4.4.2. Survey Design

Fish species richness and total fish abundance were chosen as the two ecological river quality attributes for inclusion in the CE. The benefit of adopting these attributes are three-fold. First, they can be readily linked to ecological outcomes to derive unambiguous meaningful welfare estimates (Johnston et al., 2013). Second, they lend themselves readily to benefits transfer. Finally, a framework exist for optimizing ecological outcomes such as fish species richness via river barrier mitigation (presented in Chapter 3).

In order to undertake any meaningful economic analysis of the ecological improvements associated with river barrier mitigation, it is necessary to define a list of final ecosystem services and goods on which the analysis can focus (Bateman et al., 2011). The two river attributes provide direct ecosystems services, for instance increases in wild fish species diversity and recreational angling opportunities. However, they can also be considered as biophysical inputs or intermediate services with respect to other final services (e.g., increases in the presence of iconic fish dependent species, such as Otter). Drawing on the framework presented by Bateman et al. (2011), Figure 4.1 summarizes the ecosystem goods considered most relevant to increases in fish species richness and abundance. The list of ecosystem goods presented is drawn from the UK National Ecosystem Assessment with respect to fresh waters (UKNEA, 2011). Provisioning services (i.e., fish for consumption) are not included as the main motivation for river fishing in the UK is believed to be recreation, where most anglers practice catch and release (Arlinghaus et al., 2007). However, where improved river fishing is provided, this is considered to provide recreational opportunities that promote physical and mental well-being and generate a potential source of tourism income. Given wild species diversity is valued for its existence (Krutilla, 1967), this is included as a direct ecosystem service (as per MA (2005); UKNEA (2011)). Furthermore, diverse and healthy fish populations are biophysical inputs (or intermediate services) with respect to other final services. As such, opportunities to view iconic fish dependent animals (Otter and Kingfisher) and the provision of outdoor laboratories for education and research are included amongst these services.

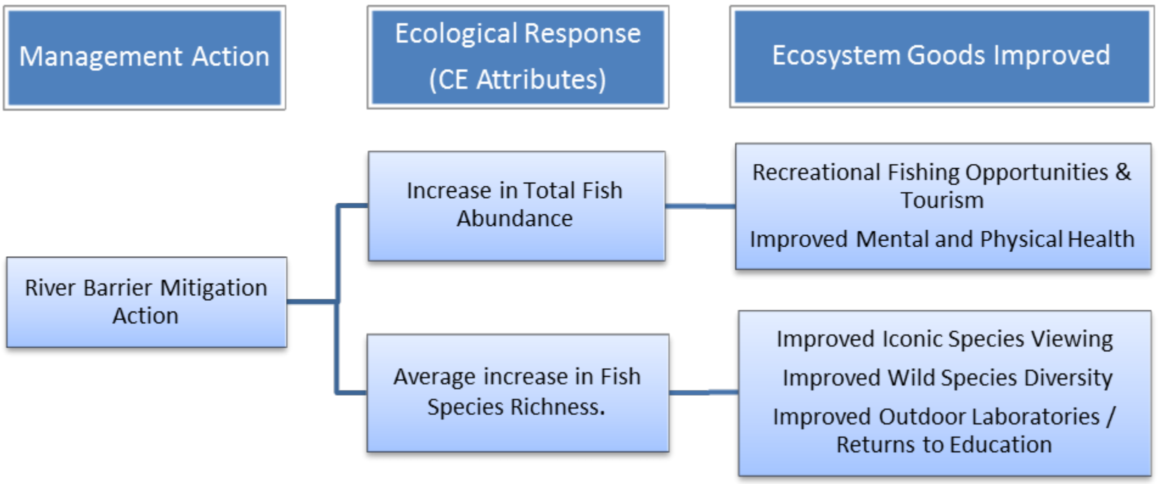


Figure 4.1.: River ecosystem services improved via river barrier mitigation actions.

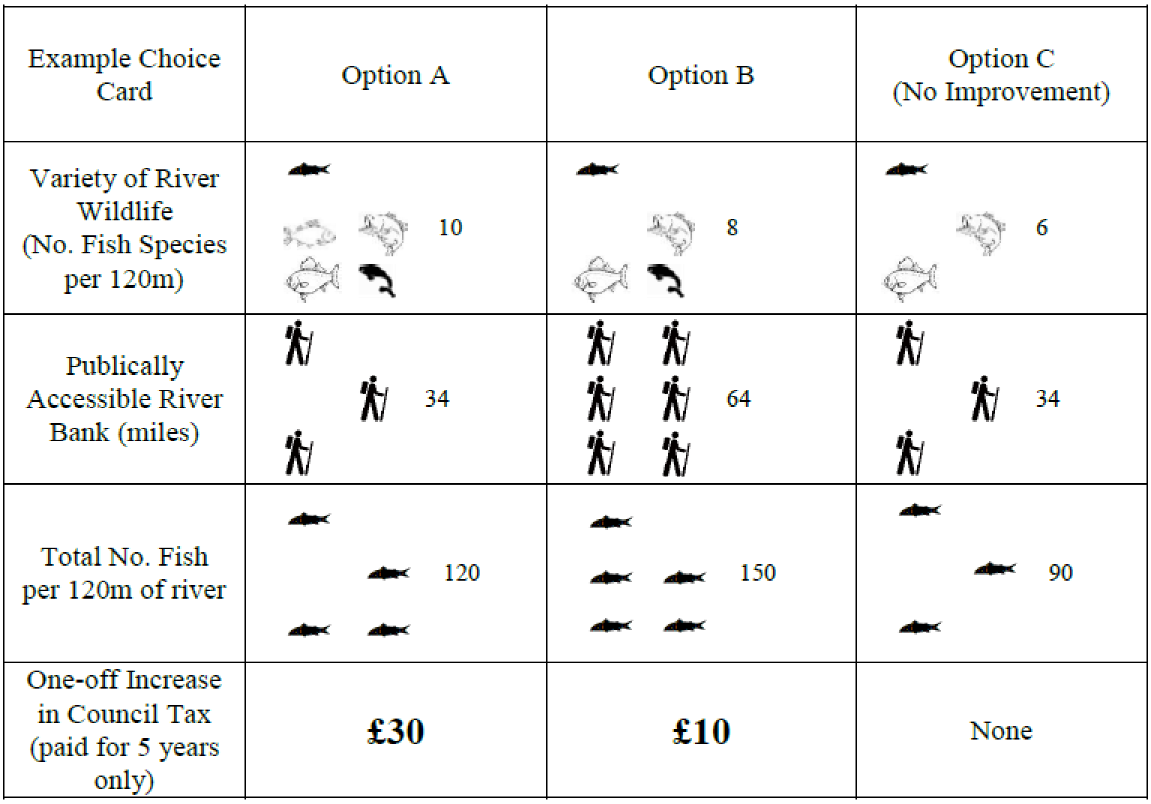
In the context of the river barrier mitigation problem, respondents face a choice between different mitigation policy options that provide different quantities of ecosystem goods presented in Figure 4.1, at varying costs. These goods and their cost comprise the attributes of the different choices (bundles) in the CE. A practical approach is adopted, where fish species richness (Var_Wild) and fish abundance (Tot_Fish) are selected as biophysical ecological river quality attributes for inclusion in the CE. In the introductory information for the CE respondents are then informed of the specific list of ecosystem goods (as per Figure 4.1) that will improve as a result of increasing the levels of these attributes. Previous studies (e.g. Morrison and Bennett, 2004; MacDonald et al., 2011) have shown that the public are able to respond to these types of biophysical attributes in a meaningful manner.

As suggested by Rolfe et al. (2002) and Hanley et al. (2010), an additional river attribute (*Access*) was included in the CE to reduce informational or focusing bias. This also avoided respondents' preferences for access becoming confounded with the ASC. Given the nature of the study, a locally administered payment vehicle is chosen for the cost attribute (*Cost*), namely a local council tax increase collected yearly for a period of five years only. The duration of the payment vehicle follows the suggestion of MacDonald et al. (2011) that a one off-payment scenario is unrealistic and conservative when benefits may accrue over many years.

A standard choice experiment utility specification was employed for the theoretical model for the choice experiment (Zhao et al., 2013). Under this approach, the respondent (on behalf of their household) is asked to choose between three options, comprising two river improvement options (A and B) that provide an increase in at least one of the attributes at a given cost and a status quo option (Option C) of no attribute improvement and zero cost. The ecological attribute levels presented in the status quo option were based on the findings of 145 fish field surveys completed by the Environment Agency at 44 locations in the River Wey between October 1989 and October 2011. The fish species richness attribute vector spanned the observed current average (status quo) to maximal observations for the river system (6, 8, 10, 12). A similar proportionate scale was adopted for the fish abundance attribute (90, 120, 150, 180). The price vector spanned zero to the estimated maximum cost of river barrier mitigation action for the river system (i.e., the cost of mitigating all known barriers / catchment population) (£0, £5, £15, £30 or £50 per household per year for five years). The access attribute was informed by the existing miles of waterway towpaths associated with the River Wey system and the additional miles of access the price vector could likely provide (34, 44, 54, 64). An example of the choice card presented to respondents is provided in Figure 4.2.

In addition to the choice task, respondents were asked questions on their use of the river, socioeconomic parameters, and protest motivations. Respondents were also asked to complete Dunlap et al. (2000) 'New Environmental Paradigm' (NEP) index in order to capture psychometric measures of environmental attitudes.

Using groups of ten, interpretation of the survey instrument was analyzed using a combination of cognitive testing (Collins, 2003) and verbal protocol analysis (Schkade and Payne, 1994) (as summarized in Appendix B). This allowed the



Example Choice Card	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	34	64	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£30**	**£10**	None

Figure 4.2.: Example choice card.

survey instrument to be developed to the point where most respondents were interpreting the scenarios and questions presented as intended. It also helped to identify if respondents suffered overly from cognitive fatigue and if any important benefits associated with river barrier mitigation action had been omitted from the survey instrument. Following this pretesting, a pilot survey was completed using 82 adults from the South East of England (as summarized in Appendix C).

A main effects factorial design was generated for the CE using the software package Ngene 1.1.1. (Choicemetrics, 2012). Priors generated from the pilot survey were used to inform the final design, which was generated by minimizing the associated D_p-error. Whilst not optimal, the final design is D-efficient (Kuhfeld et al., 1994). The final design comprised 24 different choice alternatives separated into 4 different choice blocks. Respondents were presented with one block of 6 choice alternatives and asked to complete each individually and independently. In addition, reminders to consider budget and substitutes when making choices were included (as per Mitchell and Carson, 1989). The nationally administered survey instrument was developed from the River Wey version by substituting references to the case study river with “your local river”. Apart from this, the two survey instruments were identical in every regard.[4] As such, contextual and framing effects associated

[4]The final survey instruments used in the study are presented in Appendix D (Block A only).

with the administration of the surveys across the two target populations are believed to be largely controlled for. This reflects Johnston (2007) "similarity hypothesis" that benefits transfer is likely to be valid when the policy contexts (attributes) are similar between policy and study sites. Whilst it is acknowledged that the valuation context for the national survey will vary across respondents due to the variation in proximity of a local river and any substitute rivers, it is believed that most residents in the UK have a nearby watercourse that they can readily relate to as being their "local river". This may not be the case for other environmental commodities. Furthermore, it is acknowledged that breaking the anonymity of the case study river may generate some unobservable effects. This is investigated further.

4.4.3. Survey Implementation

Both surveys were administered to a panel of online respondents using a market research company. The national generic survey was administered to a nationally representative population based on region, sex, and age. The River Wey survey was subsequently administered to postcodes within or adjacent to the River Wey catchment.

Respondents who indicated they objected to the council tax payment vehicle or did not believe the improvements offered were possible were considered protest responses and removed from both CE datasets. For the nationally administered survey, this resulted in 222 useable responses being obtained. This represented 1,322 (222 x 6) choice observations for use in estimating the choice model for the national sample. For the locally administered River Wey survey, 206 useable responses were obtained, representing 1,236 choice observations.

In order to consider socioeconomic variation, dummy variables were created for respondents with a household income over £40,000 ($High\_Inc$) and for respondents having a university degree (Deg). In order to account for respondents' use of their local river, a dummy variable was created for visitors who visited their local river on a monthly or more regular basis (Reg_Vsit). Respondents' environmental attitudes were characterized using principle components analysis to reduce Dunlap et al. (2000) NEP index to a pro-ecological attitudinal dimension (NEP) and a utilitarian view of nature dimension (DSP). The NEP values were adopted to represent a pro-ecological environmental attitude variable.

4.4.4. Utility Specifications

In order to estimate choice models in the RPL framework it is necessary to specify respondents' utility functions with respect to both the CE attributes and the influence of any relevant observed data, as per equation (4.3). Accordingly, the following general parsimonious function (Model 1) is initially specified to represent a household's deterministic utility function (V_h). In Model 1, the socioeconomic, use, and environmental attitude variables are completely omitted:

$$V_h = \beta_1 ASC + \beta_2 Var\_Wild + \beta_3 Access + \beta_4 Tot\_Fish + \beta_5 Cost \tag{4.6}$$

where: ASC is the alternative specific constant that takes the value 1 if neither of the improvement options are selected (i.e., the status quo Option C is selected); $Access$ is the miles of publicly accessible river bank; Var_Wild is the number of fish species in a length of river; Tot_Fish is the total number of fish in a length of river; and $Cost$ is the amount spent on river barrier mitigation action. For the RPL model, a normal distribution of random variables for fish species richness, access and fish abundance attributes is specified. As per Zhao et al. (2013), a non-negative bounded triangular distribution is specified for the cost attribute in order to ensure a positive marginal utility of income.

The additional socioeconomic, use, and environmental attitude variables are included in an expanded utility function (Model 2). Given that these variables remain constant for a respondent across choice occasions, a typical approach is to include them as interactions with the ASC (e.g., Colombo et al., 2007). However, this only reveals the influence of these variables on respondents preferences with respect to the status quo. The RPL specification also allows for the effect of these variables on heterogeneity with respect to the actual CE attributes to be investigated via interaction terms. As Johnston and Rosenberger (2010) observe, this results in comprehensive inclusion of additional variables in the utility specification. For instance, specifying an interaction term for the Var_Wild attribute and the NEP variable ($Var\_Wild : NEP$) reveals if the environmental attitude of a respondent is significant in explaining the strength of preference for the fish species richness attribute. Consequently, variation in the individual respondent parameter estimates for attributes (the β_{qk}'s) is generated not only through the distribution specified for the random parameter (η_q) but also the vector of the selected additional variables. Consequently, Model 2 takes the following form:

$$\begin{aligned} V_h =& \beta_1 ASC + \beta_2 ASC * High\_Inc + \beta_3 ASC * Deg + \\ & \beta_4 ASC * Reg\_Vsit + \beta_5 ASC * NEP + \beta_6 Var\_Wild \\ & + \beta_7 Access + \beta_8 Tot\_Fish + \beta_9 Cost \end{aligned} \tag{4.7}$$

In equation (4.7), individual (q) preference heterogeneity with respect to all attributes (k) is allowed to be influenced by the additional variables by specifying the individual's marginal utility for each attribute (β_{qk}) as follows:

$$\beta_{q6} = \beta_6 + \gamma_1 High\_Inc + \gamma_2 Deg + \gamma_3 Reg\_Vsit + \gamma_4 NEP + N\sigma_N \tag{4.8}$$

$$\beta_{q7} = \beta_7 + \gamma_5 High\_Inc + \gamma_6 Deg + \gamma_7 Reg\_Vsit + \gamma_8 NEP + N\sigma_N \tag{4.9}$$

$$\beta_{q8} = \beta_8 + \gamma_9 High\_Inc + \gamma_{10} Deg + \gamma_{11} Reg\_Vsit + \gamma_{12} NEP + N\sigma_N \tag{4.10}$$

$$\beta_{q9} = \beta_9 + \gamma_{13} High\_Inc + \gamma_{14} Deg + \gamma_{15} Reg\_Vsit + \gamma_{16} NEP + t\sigma_t \tag{4.11}$$

where: γ_i captures the effect of the respective variable on an individual respondent's marginal utility for the attribute, N is the standard normal distribution and t is the triangular distribution associated with the random parameters, σ_N is the standard deviation of the environmental and access parameter estimates, and σ_t is the spread of the cost parameter estimate.

4.5. Model Results

4.5.1. Observed Data

Table 4.1 presents the summary statistics and t-test results for the observed data variables collected from the national generic river and River Wey survey groups. Student's t-tests were used to establish if the mean values for these variables were statistically different between the two sample groups.

Table 4.1.: Summary Statistics for Additional Variables.

Variable	National Survey (222 Observations)		River Wey Survey (208 Observations)	
	Mean	Std. Dev.	Mean	Std. Dev.
$High\_Inc$	0.243	0.430	0.462	0.500
Deg	0.396	0.490	0.442	0.498
Reg_Vsit	0.473	0.500	0.375	0.485
NEP	0.022	1.004	0.031	0.975
t-tests				
Alternative Hypothesis (H1) tested.			t	P (t > T)
H1: Income National < River Wey Sample			-4.865	0.000***
H1: Degrees National < River Wey Sample			-0.963	0.168
H1: Regularity Visits National > River Wey Sample			2.059	0.020**
H1: NEP National < River Wey Sample			-0.086	0.466

*** significant at 1%, ** significant at 5%

Table 4.1 indicates that the income of respondents in the national sample group is lower than in the River Wey sample group and the difference is statistically significant at the 1% level. This was expected as the South East is considered a relatively affluent area compared to the rest of England and Wales. On average, respondents in the national survey visited their local river more regularly than those in the River Wey sample, the difference being significant at the 5% level. On average there are no statistically significant differences in the number of respondents with a university degree and the environmental attitude scores between the two groups. These initial results suggest that income and use of local river resources may be important in explaining differences in WTP estimates for river barrier mitigation programs between the national and River Wey sample populations.

4.5.2. RPL Model Results

In order to generate the RPL results, 500 simulated draws of random variables from their respective distributions were undertaken. All models were estimated using NLOGIT version 5 software package (Econometric Software, 2012).

4.5.2.1. National Survey Model Results

Table 4.2 shows the estimated model results for the nationally administered survey considering a generic local river. The MNL and CL model results are reported, alongside the preferred RPL model results that accommodate preference heterogeneity.

The coefficients presented in top part of Table 4.2 show how the probability of a respondent choosing any given alternative in the choice experiment varies with the level of each associated attribute or variable. A positive coefficient associated with an attribute indicates respondents are more likely to choose (or prefer) an option with a high level of this attribute. A negative value implies they are less likely to choose an option with a high level of that attribute. The ASC captures the unobservable determinants of an improvement option on the respondents' utility (i.e., those other than changes in the attribute levels) (Hanley et al., 2006). A negative value associated with the ASC indicates respondents are more likely to choose an improvement option for barrier mitigation (option A or B) over the status quo (Option C). A negative value associated with an $ASC : Variable$ interaction indicates respondents are more likely to choose an improvement option as the level of that variable increases. A negative ASC can also be interpreted as respondents being willing to pay for an improvement option for reasons other than improvements in the attributes offered in the CE.

The coefficients on all attributes across all model specifications are consistently statistically significant at the 1% level and have expected signs. For example, the positive coefficient for the Var_Wild attribute reflects the *a priori* expectation that choice options which increase the variety of wildlife in rivers are more likely to be chosen. The negative sign on the $Cost$ coefficient conforms to economic theory that rational respondents are less likely to choose options with a higher cost, *ceteris paribus*. The RPL model specifications summarized in Table 4.2 are statistically significant at the 1% level.

The ASC is found to be insignificant in the MNL and CL Model specifications. For the preferred RPL specifications the ASC is found to be negative and significant, this reveals that there exists unobserved motivations across respondents for

Table 4.2.: Model Results National Survey (1,332 Choice Observations)

Variable	MNL Model 1		RPL Model 1		CL Model 2		RPL Model 2	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
ASC	-0.080	0.138	-0.546**	0.234	-0.108	0.169	-0.835**	0.375
Var_Wild	0.180***	0.018	0.256***	0.038	0.180***	0.018	0.292***	0.058
$Access$	0.038***	0.004	0.049***	0.007	0.038***	0.004	0.051***	0.011
Tot_Fish	0.011***	0.001	0.016***	0.003	0.011***	0.001	0.015***	0.004
$Cost$	-0.049***	0.003	-0.093***	0.013	-0.049***	0.003	-0.115***	0.020
$ASC : NEP$					-0.357***	0.076	-0.102	0.205
$ASC : Deg$					0.385**	0.160	1.107**	0.452
$ASC : High\_Inc$					0.341*	0.177	-0.282	0.481
$ASC : Reg\_Vsit$					-0.656***	0.162	-0.594	0.413
Standard Deviation								
Var_Wild			0.071	0.171			0.061	0.183
$Access$			0.058***	0.019			0.051**	0.021
Tot_Fish			0.027***	0.006			0.027***	0.006
$Cost$			0.093***	0.013			0.115***	0.020
Log Likelihood	-1091.388		-1073.678		-1061.175		-1025.019	
Pseudo R^2			0.266				0.300	
AIC	2192.8		2163.4		2140.4		2106.0	

*** significant at 1%, ** significant at 5%, * significant at 10%

choosing river improvement options. This could infer that an important attribute has been omitted from the experiment and heuristic approaches are being employed during the choice task by respondents seeking to increase provision of this attribute. However, given the repeated testing and piloting of the survey instrument, it is anticipated that any such attribute would have been identified. It is considered more likely that the negative ASC has emerged as a result of a latent variable, reflecting respondents motivations for improvement of local river environments for altruistic reasons. This can be likened to a desire for local stewardship or the 'warm glow' effect described more generally in the literature (e.g., Nunes and Schokkaertd, 2003). A final possibility is the negative ASC reflects an element of 'yea-saying' to improvement choices, as Morrison et al. (2002) discuss. These issues are given further consideration during the analysis of the pooled data results.

Regarding the ASC : variable interactions, the CL Model 2 specification confirms the *a priori* expectation that respondents with higher NEP scores and who regularly visit the river are more likely to choose an improvement option over the status quo. Generally, it is expected that highly educated respondents with higher incomes would be more willing and able to pay for an improvement option, however, in both cases the results of CL specification for Model 2 find the converse to be true. The RPL Model 2 specification also confirms that respondents with a university degree are more likely to choose the status quo option. The RPL Model 2 did not identify environmental attitude, income, or regularity of visit to have a significant effect on choosing an improvement option over the status quo. This suggests that choice models that impose homogeneous preferences or restrict the inclusion of socioeconomic (and other) variables to ASC interactions may be inappropriate, as their influence is confined to modeling the respondent's departure from the status quo choice. This may prove particularly misleading in CEs where the status quo option is rarely chosen.

For both the RPL Model 1 and RPL Model 2 specifications, the standard deviation in the random parameter for the Var_Wild attribute was statistically insignificant. This suggests that preferences for this attribute may be homogenous across the national sample. The deviating measures for the $Access$, Tot_Fish and $Cost$ attributes were all found to be significantly different from zero at the 5% level. The pseudo R^2 for the RPL Model 2 (0.30) meets a general benchmark of explanatory power generally considered acceptable for discrete choice models (Hensher et al., 2005).

4.5.2.2. National Survey Heterogeneity Results

In order to present a comprehensive assessment of heterogeneity in the RPL Model 2 specification, interaction terms are specified for all four socioeconomic, use, and environmental attitude variables and all four choice experiment attributes. Results for the significant interactions only are summarized in Table 4.3.

Table 4.3.: Significant Heterogeneity Variables, National RPL Model 2

Attribute : Variable Interaction	Heterogeneity in Mean	S.E.
Var_Wild : Reg_Vsit	-0.124**	0.061
Tot_Fish : NEP	0.004*	0.002
$Cost$: NEP	0.012**	0.006
$Cost$: Deg	0.022*	0.012
$Cost$: $High\_Inc$	-0.028**	0.014
$Cost$: Reg_Vsit	0.025**	0.012

*** significant at 1%, ** significant at 5%, * significant at 10%

The heterogeneity in mean values provided in Table 4.3 explain how variation in marginal utilities for a given attribute across individuals may be explained by differences in the variable in the associated interaction term. For instance, the positive and significant value for the Tot_Fish : NEP term indicates that respondents with higher NEP scores are more likely to pick options that increase the number of fish in the local river (i.e., they have individual coefficients that are more positive for this attribute), which meets the *a priori* expectation. The negative value for the Var_Wild : Reg_Vsit term indicates that respondents who visit their local river regularly will be less sensitive to increases in the fish species richness attribute when making their choices (i.e., they have marginal utilities that are closer to zero for this attribute). This suggests preferences towards this attribute are influenced by non-use motivations, despite the associated increased potential for iconic species viewing during visits to the river. Despite this observation, it is noted the RPL Model results reported in Table 4.2 indicate an absence of significant preference heterogeneity across the sample group with respect to the Var_Wild attribute.

Interpretation of the *Cost* : *Variable* interaction terms is reversed given that the coefficient for the cost attribute is negative. The negative and significant value for the *Cost* : $High\_Inc$ term indicates that respondents with a higher income are actually more sensitive to price and will be less likely to choose an option with a higher cost (i.e., they have individual coefficients that are more negative for this attribute, indicating a higher marginal utility of income in the context of the choice experiment). This is counter intuitive as it would be expected that respondents with a higher income would be less sensitive to price. The positive values for the *Cost* : NEP, *Cost* : *Degree* and *Cost* : Reg_Vsit interaction terms indicate that respondents with higher NEP scores, a university degree, or who visit the local river regularly are less sensitive to increases in the cost attribute when making their choices (i.e., they have individual coefficients for the cost attribute closer to zero, indicating a lower marginal utility of income).

The overall picture that emerges is that preferences for the cost attribute are most influenced by the socioeconomic, environmental attitude, and use variables. This may be driven by variations in attribute attendance, with high income earners more attentive to the *Cost* attribute and respondents who are more educated, have more pro-ecological attitudes, and use their local river more regularly less focused on the *Cost* attribute. It is noted that the socioeconomic variables (income and education) do not significantly explain heterogeneity in respondent's preferences for the *Tot_Fish* and *Access* attributes. Interestingly, preferences for the *Var_Wild* attribute appear to be homogeneous across catchments.

4.5.2.3. River Wey Survey Model Results

Table 4.4 shows the estimated model results for the River Wey survey. The coefficients on all attributes across all model specifications are generally statistically significant at the 1% level, the only exception being for the *Access* attribute in RPL Model 2 (significant at the 5% level). All attribute coefficients have their expected signs, reflecting *a priori* expectations. The RPL model specifications summarized in Table 4.4 are statistically significant at the 1% level.

Again the ASC is negative and significant in all of the model specifications, indicating unobserved motivations exist for choosing local river improvement options amongst respondents living close to the River Wey. It is also noted that the *ASC* for the RPL Model specifications for the River Wey sample is 2 – 3 times greater than that for the national generic river sample.[5] Given the magnitude of this difference, it is considered likely that the negative ASC is being driven by some underlying variable that is perceived to vary substantially between the two sample groups. This also provides some confidence that the negative ASC is not predominantly an artifact of respondent 'yea-saying'. This is discussed further in an analysis of the pooled data.

The CL Model 2 specification confirms the *a priori* expectation that respondents with higher *NEP* scores and incomes are more likely to choose an improvement option over the status quo, as they are more concerned with environmental issues and are more likely to be able to afford it. As with the national survey, the CL Model identified that respondents with a university degree are less likely to choose an improvement option over the status quo. The RPL Model 2 specification did not identify having a university degree, high income, positive environmental attitude, or regularly visiting the river to have a significant effect on choosing an improvement option over the status quo. This again suggests that choice models that impose homogeneous preferences or restrict the inclusion of socioeconomic (and other) variables to ASC interactions may be inappropriate. Both the RPL Model 1 and RPL Model 2 confirm the statistical significance of the deviating measures for all four attributes at the 5% level or greater, implying significant heterogeneity of preferences. Surprisingly, in comparison with the national survey results, this suggests that heterogeneity with respect to the *Var_Wild* attribute is more of an issue for within catchment populations than between catchment populations. The pseudo R^2 for RPL Model 1 (0.32) and RPL Model 2 (0.34) meet the 0.30 benchmark of explanatory power for discrete choice models. The slightly higher explanatory power

[5] It should be noted that on the basis of overlapping 95% confidence intervals these large absolute differences observed are not confirmed to be statistically different.

Table 4.4.: Model Results for River Wey Survey (1,248 choice observations)

Variable	MNL Model 1		RPL Model 1		CL Model 2		RPL Model 2	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
ASC	-0.873***	0.142	-1.885***	0.440	-0.754***	0.176	-1.847***	0.473
Var_Wild	0.178***	0.018	0.293***	0.054	0.178***	0.018	0.236***	0.059
Access	0.030***	0.004	0.043***	0.008	0.030***	0.004	0.022**	0.010
Tot_Fish	0.006***	0.001	0.011***	0.003	0.007***	0.001	0.011***	0.004
Cost	-0.058***	0.003	-0.124***	0.022	-0.058***	0.003	-0.111***	0.021
ASC : NEP					-0.159*	0.086	0.116	0.220
ASC : Deg					0.427**	0.181	0.317	0.457
ASC : High_Inc					-0.516***	0.184	-0.198	0.456
ASC : Reg_Vsit					-0.268	0.186	0.239	0.460
Standard Deviation								
Var_Wild			0.382***	0.119			0.335***	0.109
Access			0.068***	0.023			0.060***	0.021
Tot_Fish			0.020***	0.007			0.017***	0.006
Cost			0.124***	0.022			0.111***	0.021
Log Likelihood	-948.369		-929.207		-940.842		-911.130	
Pseudo R^2	1906.7		1874.4		1899.7		1878.3	
AIC			0.322				0.335	

*** significant at 1%, ** significant at 5%, * significant at 10%

of the River Wey RPL models compared to the national models may be a result of the scenario being viewed as more realistic to respondents due to the naming of the river.

4.5.2.4. River Wey Survey Heterogeneity Results

As with the national survey, interaction terms are specified for all four socioeconomic, use and environmental attitude variables and all four choice experiment attributes to explore the influence of these variables on preferences heterogeneity. Results for the significant interactions only are summarized in Table 4.5.

Table 4.5.: Significant Heterogeneity Variables, River Wey RPL Model 2

Attribute : Variable Interaction	Heterogeneity in Mean	S.E.
Access : High_Inc	-0.028**	0.014
Cost : Deg	0.024*	0.013
** significant at 5%, * significant at 10%		

The negative and significant value for the *Access : High_Inc* term indicates that respondents with a higher income are less likely to choose an option that increases access. This suggests that high income earners are less concerned about access to the River Wey for leisure, possibly due to being able to afford more expensive pursuits. The positive value for the *Cost : Deg* interaction term indicates that respondents with a university degree are less sensitive to increases in the cost attribute when making their decisions.

The overall picture that emerges is that whilst there is significant heterogeneity in preferences for all four attributes in the River Wey sample, this is not particularly well explained by variations in socioeconomic, environmental attitude, or use variables. This is particularly the case for the ecological attributes and may indicate that the additional motivations that emerge for river barrier mitigation in the River Wey once its anonymity is broken (as discussed with respect to the ASC) may vary significantly across individuals. The significance of these types of scale effects on respondents' marginal utilities for CE attributes cannot be evaluated using the RPL framework.

4.5.2.5. Pooled Data Analysis

Given that the CEs administered nationally and locally to the River Wey share a common design, they can be readily pooled to form a single dataset. Consequently, heterogeneity in preferences for the CE attributes between the two survey groups can be investigated by specifying a dummy variable identifying the River Wey survey responses (*Riv_Wey*) and then investigating the significance of this variable in the analysis of the pooled dataset. Accordingly, RPL Model 2 is revised to include the additional $ASC : Riv\_Wey$ interaction term. In addition, the vector of individual respondents' marginal utilities for the CE attributes (i.e., $\boldsymbol{\beta}_q$) is now also conditioned on the Riv_Wey dummy variable (in addition to the NEP, $High\_Inc$, Deg, Reg_Vsit dummy variables). Table 4.6 shows the estimated results for this revised RPL 2 specification. Only the significant interactions are presented.

The sign and significance of the parameter estimates presented in Table 6 are generally as expected given the results obtained from the individual survey analysis. The coefficient for the $Tot\_Fish : Riv\_Wey$ term reported in Table 4.6 is negative and significant, confirming that the River Wey respondents had preferences for the Tot_Fish attribute closer to zero. The negative sign and high significance of the $ASC : Riv\_Wey$ interaction term indicates that respondents to the River Wey survey are willing to choose river improvement options for reasons other than the improvements in the environmental and access attributes offered (i.e., the unobserved influences motivating choices to improve the river are more pronounced). This meets the *a priori* expectation given the relative magnitude of the ASC terms previously estimated for the individual survey groups. There is no reason to to believe there will be a statistically larger number of 'yea-sayers' for improvement programs in the River Wey sample group. Furthermore, the important attributes of choice are believed to have been identified during the survey development stage. Consequently, the significance of the $ASC : Riv\_Wey$ interaction term is considered indicative of a latent variable whose magnitude varies between the two CE contexts. It is believed this reflects an altruistic local stewardship motivation that increases once the anonymity of the river is broken. Jaconsen et al. (2008) similarly find increased preferences for securing habitat for endangered species when the species are named rather than considered generically.

Hensher (2012) observes that when combining different survey datasets, consideration of the variance associated with the scale of the unobserved influences on choice (i.e., those captured by the ASC) is required. The significance of scale heterogeneity between the national and River Wey datasets can be investigated using the G-MNL-II framework proposed by Fiebig et al. (2010), as discussed in Section 4.3.3. The G-MNL-II specification is particularly useful in this regard as an individual respondent's scale parameter $\sigma_q = \exp\left({}^{-\tau^2}/_2 + \boldsymbol{\theta z}_q + \tau\varepsilon_{0q}\right)$ within the pooled dataset can be conditioned by specifying $\boldsymbol{z}_q$ as a dummy variable indicating membership of the River Wey sample population (i.e., Riv_Wey). Accordingly, the magnitude and significance of the differences in scale heterogeneity between the groups can be assessed via the associated heterogeneity parameter θ. The presence or absence of general scale heterogeneity across respondents in the pooled dataset is revealed by the significance of the global scale parameter τ. Table 4.7 summarizes the results of estimating the RPL Model 2 specified in Section 4.4.4 using the G-MNL-II framework for the pooled data. For the sake of brevity the interaction terms between the attributes and observed data variables are omitted.

Table 4.6.: RPL Model Results for Pooled Data (2,580 Choice Observations)

Variable	Parameter Estimates Coef.	Parameter Estimates S.E.	Attribute : Variable Interaction	Heterogeneity in mean Coef.	Heterogeneity in mean S.E.
ASC	-0.829**	0.325	*Var_Wild* : *NEP*	0.039*	0.023
Var_Wild	0.284***	0.049	*Tot_Fish* : *NEP*	0.004**	0.002
Access	0.043***	0.009	*Tot_Fish* : *Riv_Wey*	-0.007**	0.003
Tot_Fish	0.016***	0.003	*Tot_Fish* : *Reg_Vsit*	0.005*	0.003
Cost	-0.112***	0.016	*Cost* : *NEP*	0.008*	0.004
ASC : *Riv_Wey*	-1.070***	0.315	*Cost* : *High_Inc*	-0.016*	0.009
ASC : *NEP*	0.009	0.150	*Cost* : *Reg_Vsit*	0.022**	0.009
ASC : *Deg*	0.761**	0.322			
ASC : *High_Inc*	-0.248	0.336			
ASC : *Reg_Vsit*	-0.154	0.308			
Standard Deviation			Model parameters		
Var_Wild	0.269***	0.081	Log Likelihood	-1,961.017	
Access	0.064***	0.016	Pseudo R^2	0.308	
Tot_Fish	0.020***	0.005	AIC	3,988.0	
Cost	0.112***	0.016			

*** significant at 1%, ** significant at 5%, * significant at 10%

Table 4.7.: Results of Interest from G-MNL-II Model

Variable	Parameter Estimates		Model Parameters	Value	S.E.
	Coef.	S.E.			
ASC	-0.476**	0.194	τ	0.909***	0.164
Var_Wild	0.242***	0.058	θ	0.129	0.102
Access	0.045***	0.011	Log Likelihood	-1991.52	-
Tot_Fish	0.013***	0.004			
Cost	-0.093***	0.019	Pseudo R^2	0.297	-
ASC : NEP	-0.071	0.115	AIC	4043.0	-
ASC : Deg	0.395*	0.240			
ASC : High_Inc	-0.223	0.254			
ASC : Reg_Vsit	-0.324	0.234			
Standard Deviation					
Var_Wild	0.094	0.219			
Access	0.167***	0.054			
Tot_Fish	0.097***	0.018			
Cost	0.093***	0.019			

*** significant at 1%, ** significant at 5%, * significant at 10%

Table 4.7 reveals that the parameter estimates for the CE attributes are very similar to those estimated using the RPL model reported in Table 4.6. Given the absence of the *ASC : Riv_Wey* interaction term in the G-MNL-II model specification, the ASC terms are not directly comparable between the two models.

The global scale factor τ is noted to be highly significant, confirming the presence of scale heterogeneity across individuals in the pooled dataset. However, as θ is not significantly different from zero, the observed scale heterogeneity is not generally explained by whether an individual is a member of the River Wey survey group or the national survey group. Consequently, it can be assumed that the significant differences in preferences towards the *Tot_Fish* attribute (i.e. individual marginal utilities close to zero) exhibited by members of the River Wey survey group arise from members of this group having a reduced taste preference for total fish increases rather than being an artifact of the differences in the unobserved influences on choice across the two survey groups.

An interesting observation with respect to Table 4.7 is that the standard deviation of the random parameter for *Var_Wild*, and hence heterogeneity with respect to this attribute, is statistically insignificant. Thus, the heterogeneity identified with respect to *Var_Wild* in Table 4.6 when estimating the RPL model ceases to be significant once scale is controlled for within and between datasets. Consequently, it appears to be the case that it is the unobserved influences on choice (i.e., those captured by the ASC) rather than actual taste preferences for the *Var_Wild* attribute that generates the preference heterogeneity observed across individuals in the pooled datasets. This supports the notion that taste preferences for the Var_Wild attribute are generally consistent both between and within catchments. Whilst not reported here, it is noted that estimating the RPL Model 2 specification (Section 4.4.4) for the River Wey survey dataset using the G-MNL-II framework did not identify significant preference heterogeneity with respect to the Var_Wild attribute, providing further support for this argument. As noted in Section 4.5.2.1, preferences for the Var_Wild attribute were not heterogeneous in the national survey dataset. Overall this suggests that an implicit price (IP) for the Var_Wild attribute may be suitable for direct transfer between catchments.

4.6. Welfare and Benefits Transfer Analysis

The marginal WTP or IP for an increase in the level of any given attribute is given by the negative of the ratio of the coefficient for that attribute (β_k) and the coefficient for the cost attribute (β_c) (i.e., $IP = \beta_k/\beta_c$). Colombo and Hanley (2008) suggest that whilst IPs are useful to policy makers for defining priorities for action, they do not represent valid welfare measures to be used in CBA. However, in order to generate full compensating surplus for a policy package, it is necessary to include the welfare effect captured by the ASC. The inclusion of this effect requires an assumption that the unobserved determinants of utility associated with river barrier mitigation (i.e., those not covered by attributes) will be the same when moving from the national generic setting to the local context (i.e., scale is not significantly different). As the ASC is found to increase by a factor of 2 to 3 when moving from the national to the River Wey context and the $ASC : Riv\_Wey$ interaction term is significant in the pooled data analysis, this assumption appears invalid. This reveals that stronger unobserved motivations emerge for choosing river improvement options in the CE when the local river is named. It is suggested that this arises from increases local stewardship once the anonymity of the river is broken.

Whilst the G-MNL-II model indicates that marginal utilities for the CE attributes are not significantly affected by scale differences between the two datasets, these unobserved influences are clearly significant in explaining preferences to depart from the status quo (i.e., chose an improvement option). Morrison et al. (2002) suggest in contexts where catchments may differ substantially in unobserved aspects, it may be prudent to rely solely on the IPs. Furthermore, it should be noted that the ASC was negative in all cases. This indicates that relying solely on IPs will generate conservative benefit estimates, as respondents are consistently willing to pay for river barrier mitigation action for reasons other than fish population and associated ecosystem services improvements. Furthermore, the inclusion of the welfare effect captured by the ASC may be spurious, as it is unclear if this benefit would actually be delivered under a barrier mitigation program. Considering the above, it is considered appropriate to restrict the welfare and benefits transfer analysis to the consideration of implicit prices. This will also help to purge any minor erroneous contributions of 'yea-saying' to welfare estimations.

4.6.1. Implicit Prices

The Wald test statistic was used to establish if the IPs for the attributes in both the national and River Wey samples were significantly different from zero. The IPs for the ecological attributes for the National, River Wey, and pooled samples are presented in Table 4.8. Due to the preference heterogeneity observed, only IPs estimated from the RPL and G-MNL-II specifications are reported. The standard errors of the maximum likelihood estimates of the IPs are also presented, along with associated 95% confidence intervals.

The first observation that can be made with respect to Table 4.8 is that the implicit prices for the ecological attributes are statistically significant and positive at the 99% confidence level and the access attributes at the 95% confidence level or greater. For the individual CEs, the IPs are also consistently higher in the RPL Model 1 specification, where the socioeconomic, environmental attitude, and use variables are omitted from the utility specification.

Table 4.8.: Implicit Prices

Attribute	IP (£/yr)	S.E.	95% Conf. Int		IP (£/yr)	S.E.	95% Conf. Int	
	National RPL Model 1				River Wey RPL Model 1			
Var_Wild	2.77***	0.34	2.09	3.44	2.36***	0.29	1.79	2.92
Access	0.53***	0.07	0.39	0.68	0.34***	0.06	0.21	0.47
Tot_Fish	0.18***	0.02	0.14	0.22	0.09***	0.02	0.05	0.12
	National RPL Model 2				River Wey RPL Model 2			
Var_Wild	2.53***	0.45	1.66	3.40	2.12***	0.46	1.21	3.02
Access	0.44***	0.10	0.25	0.63	0.20**	0.09	0.01	0.38
Tot_Fish	0.13***	0.03	0.07	0.18	0.10***	0.03	0.04	0.16
	Pooled RPL Model				Pooled G-MNL-II Model			
Var_Wild	2.54***	0.39	1.78	3.31	2.61***	0.36	1.90	3.32
Access	0.38***	0.08	0.22	0.55	0.48***	0.09	0.31	0.65
Tot_Fish	0.15***	0.03	0.10	0.20	0.14***	0.02	0.09	0.18

*** significant at 1%, ** significant at 5%, * significant at 10%

Given the particular interest in the ecological attributes, the following discussion focuses on the *Var_Wild* and *Tot_Fish* attributes, rather than *Access*. For both the RPL Model 1 and RPL Model 2 specifications, the confidence intervals for the IPs for the *Var_Wild* for the national and River Wey samples are found to overlap. This suggest these IPs may not be statistically different. In fact the IPs are quite similar. This is as expected given preferences for this attribute appear more stable between and within the two sample datasets. These results are generally supportive of the transfer of the nationally derived generic IP for the Var_Wild attribute to the River Wey catchment.

The results are somewhat mixed for the IPs for the Tot_Fish attribute. In the RPL Model 1 specification the confidence intervals do not overlap. However, for the RPL Model 2 specification (when additional variables enter the utility specification), the results are more promising; the confidence intervals overlap and the IPs only vary by only 30%. This is initially surprising as there are statistically significant differences in the patterns of use and income between the two groups. Consequently, allowing these differences to enter the utility specification for the model would be expected to promote divergence rather than convergence in IPs. Whilst these variables were not found to be significantly influential in the context of the River Wey, they were with respect to the cost attribute in the national sample.

The IPs generated via the RPL and G-MNL-II models using the pooled data are higher than those for the River Wey sample and lower than those for the national sample estimated via RPL Model 1, as would be expected. Somewhat surprisingly, the IPs from the pooled dataset are higher than those estimated for both the River Wey and national datasets using the RPL Model 2 specification, albeit only very marginally and insignificantly.[6]

It is noted that the G-MNL-II model estimated in Section 4.5.2.5 identified significant scale heterogeneity across individuals ($\tau = 0.909$, $p < 0.01$). However, the IPs for the Var_Wild and Tot_Fish attributes estimated using the G-MNL-II specification (as reported in Table 4.8) are very similar to those estimated via the pooled RPL Model. Hensher (2012) observes a similar result with respect to travel time savings when combining stated and revealed preference datasets and modeling scale heterogeneity within the pooled data but not between the different datasets.[7] In his analysis, Hensher (2012) suggests that when τ is fed into the calculation of $\sigma_q = \exp\left(-\tau^2/2 + \boldsymbol{\theta z}_q + \tau\varepsilon_{0q}\right)$[8] the standard deviation term (σ_q) is not significantly different from unity. A similar scenario is believed to be occurring here when estimating the G-MNL-II model using the pooled dataset. This implies that in this instance, the G-MNL-II model described in Section 4.3.3 essentially resolves to the standard RPL model described in Section 4.3.2, at least with respect to parameter estimates for the ecological and cost attributes.

4.6.2. Equivalence Test

Whilst overlapping confidence intervals are useful in providing an initial insight into how suitable the generic national IPs are for transfer to the case study river, further analysis is required in order to estimate the expected magnitude of error associated

[6]On the basis of confidence intervals, the means overlap considerably.

[7]This is analogous to the G-MNL-II model specification evaluated herein given θ is not significantly different from zero.

[8]Where $\boldsymbol{\theta z}_q$ is dropped given θ is not significantly different from zero.

with this practice. Equivalence tests have been used in pharmaceutical research for these types of analysis for a number of years and are now being employed in benefit transfer studies (e.g., Hanley et al., 2006b). Equivalence tests examine if the difference in means between two sample datasets is less than some predetermined amount at a given level of significance. Kristofersson and Navrud (2005) present a summary of the technique in the context of environmental benefits transfer. In this case, determining if the differences in mean IPs estimated for the River Wey CE varies by no more than a given amount (Δ) from those generated from the national CE at a reasonable level of confidence is of interest. Typically Δ is assumed to be 20% in pharmaceutical studies, where a high degree of equivalence is often required (Kristofersson and Navrud, 2005). The two one-sided test (TOST) is a simple version of an equivalence test that consists of two one-side t-tests at a chosen level of significance (α). Richter and Richter (2002) present a good overview of the method to generate the test statistics, which can be expressed as shown below:

$$t_1 = \frac{D - \Delta}{\sqrt{S_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \leq -t_{1-\alpha} \qquad t_2 = \frac{\Delta + D}{\sqrt{S_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \geq t_{1-\alpha} \tag{4.12}$$

where: $t_{1-\alpha}$ is the t-value associated with the chosen significance level (α) and degrees of freedom, D is the absolute difference in the mean IP estimates, S_p^2 is the variance of the pooled IP estimates and n_1 is the number of IP estimates for the National CE and n_2 is the number of IP estimates for the River Wey CE.

Investigating if the nationally derived IPs can be transferred to other catchments for which there is no data on benefiting populations (e.g., individuals socioeconomic, environmental attitude, or river use characteristics) is of particular interest here. Consequently, the IPs generated using the parsimonious RPL Model 1 specification are those that should be tested for equivalence, as these were estimated without recourse to these additional variables. In order to generate a set of IP observations for the Var_Wild and Tot_Fish attributes, the RPL Model 1 is re-estimated a total of 200 times for both the national and River Wey CE survey results. This allows a series of different draws of random parameters from the specified distributions to be undertaken. In order to limit the time for generating these datasets, the number of simulated draws for each model estimation is restricted to 200. This approach is analogous to the Krinsky and Robb (1986) procedure but without the limitations of assuming a normal distribution for the cost parameter. The 200 WTP estimates for both samples implies 398 degrees of freedom (200 + 200 − 2) and associated critical t values (t_{crit}) of 1.66 at the 95% confidence level. A number of different variation amounts (Δ) are explored in order to identify the difference that will not be exceeded at the 95% confidence level. The results of the TOST equivalence test are presented in Table 4.9.

It is noted that the mean IP estimates and associated standard errors reported in Table 4.9 are very similar to those reported in Table 4.8, demonstrating convergent validity. This is reassuring as the Wald test procedure employed to generate the IPs presented in Table 4.8 assumes the IPs are approximately normally distributed. A number of authors suggest this may not be the case for WTP estimations based on a ratio of parameter distributions. Hensher and Greene (2003) present a discussion of these types of issues.

Table 4.9.: TOST Equivalence Test Results

Attribute	National IP (£/yr)		River Wey IP (£/yr)		D	Δ	t_1	t_2
	Mean	S.E.	Mean	S.E.	(%)	(%)		
Var_Wild	2.745	0.429	2.380	0.292	13	20**	-5.01	24.91
						35**	-16.24	36.13
						50**	-27.46	47.35
						75**	-46.16	66.05
						100**	-64.86	84.75
Tot_Fish	0.178	0.027	0.086	0.020	52	20	23.73	53.71
						35	12.50	64.94
						50	1.26	76.18
						75**	-17.47	94.91
						100**	-36.19	113.64

** Equivalent at the specified Δ at 95% confidence level ($t_1 < t_{crit95}$ & $t_2 > t_{crit95}$),

The equivalence test results confirm the generic IP for the *Var_Wild* attribute is robust. The estimate for the River Wey is shown to be within 20% of the generic national estimate at the 95% confidence level. As expected, the generic IP for the *Tot_Fish* attribute is less robust, although the IP estimated for the River Wey is still shown to be within 75% of the generic national IP at the 95% confidence level. For the purposes of estimating the benefits of river barrier mitigation program, these levels of equivalence confidence may be acceptable to decision makers.

The larger transfer error associated with the IP for *Tot_Fish* reflects the heterogeneity in preferences discussed with respect to this attribute both within and between the two survey groups. The analysis of the pooled data identified respondents to the River Wey survey had significantly smaller marginal utilities for this attribute. It may be that as respondents from this survey group had generally higher incomes and visited their local river less compared to the national survey group they may be interested in more expensive pursuits than fishing. In addition, as the improved fishing opportunities provided by this attribute were also linked to potential recreational and local economic benefits for others, there may be reduced altruistic motivations to provide these for other community members within the River Wey sample group given the general affluence of the area. This implies the WTP for ecosystem goods linked to community benefits would be expected to vary across populations due to variations both recreational pursuits and social norms between different communities.

4.6.3. Latent Class Welfare Analysis

A Latent Class Model (LCM) was estimated for each of the national, River Wey and pooled datasets in order to provide alternative WTP estimates to those presented in Section 4.6.2. Under this approach instead of allowing parameter estimates to vary across all individuals in the choice experiment sample (i.e., $\boldsymbol{\beta}_q$), the sample is split into a number of latent classes l, as specified by the analyst. The model then estimates parameters for each class (i.e., $\boldsymbol{\beta}_l$ values). The significance of observed data on the probability of a respondent being a member of a given class can also be investigated in the LCM framework.

On the basis of the best model fit (minimal AIC value) three latent classes were specified for modeling all three datasets. For each dataset three similar groups emerged: one of between 35% and 40% of respondents with high and significant WTP measures for both ecological attributes; one of between 10% and 15% with very low or zero WTP for ecological attributes; and, the remainder having low but significant WTP for the ecological attributes.

The class weighted average IP for the Var_Wild attribute estimated for the national sample was £5.39 and for the River Wey sample was £4.51. In relative terms these estimates are similar, the River Wey IP is only around 15% lower than the national generic IP. This again suggesting that IPs for fish species richness are suitable for direct transfer. The weighted average IP for the Tot_Fish attribute was £0.36 from the national sample and £0.22 from the River Wey sample. In relative terms the difference in IPs is quite large, the River Wey IP is around 40% lower than the national IP. This again confirms that that the attribute for fish abundance will not be robust to direct transfer. It is also noted that the LCM estimates are approximately two times greater than those estimated using the RPL and G-MNL-II specifications. This suggests that the imposition of constraints on preference heterogeneity may lead to over estimates of benefit values in the context of river barrier mitigation.

The effect of socioeconomic variables was explored in the national context. Having a degree (Deg) provided conflicting insights, being significant in explaining membership of both the high and very low to zero WTP groups. Counter intuitively above average income ($High\_Inc$) was significant in explaining membership of the very low to zero WTP group. As with the RPL and G-MNL-II analyzes, the LCM identifies socioeconomic variables provide to provide conflicting insight into WTP, again suggesting they are unlikely to successfully explain benefit transfer error in the context of river barrier mitigation. For both the national and River Wey sample groups, having a pro-ecological attitude (NEP) was a significant predictor of membership of the high WTP for ecological attributes class.

4.7. Conclusions

This chapter presents the findings of choice experiments (CE) to estimate the benefits of improvements in river ecosystem service delivery resulting from river barrier mitigation, specifically via increases in fish species richness (Var_Wild) and fish abundance (Tot_Fish). Initially a CE considering a generic local river is administered to a nationally representative sample, this is followed up by administering the same CE but for a case study river (the River Wey, South East England) to a sample of local residents. The two sample groups are found to differ significantly in terms of income and use of their local river.

Analysis of the CE results showed respondents in both sample groups have preferences for increasing fish species richness and abundance, which are significant at the 1% level. The inclusion of socioeconomic, use, and environmental attitude variables was found to increase the explanatory power of the CE models. Alternative specific constants (ASCs) are found to be consistently statistically significant and negative across both sample groups, indicating respondents have a general preference for river improvement. Analysis of the pooled survey data revealed that respondents from the River Wey sample had significantly more negative ASCs and were, consequently, willing to pay more for river improvement options for reasons other than the improvements in fish species richness, fish abundance and access. This suggests that the unobserved motivations for choosing river barrier mitigation options are greater when the anonymity of the river is broken. It is speculated that this may be the result of ‘local stewardship’ motivations. Having a university degree was found to be associated with status quo bias in the national sample, which was an unexpected result. A similar result was found when analyzing the pooled dataset.

For both samples, neither income nor having a university degree had a significant effect on the marginal utility of the ecological attributes. For both the national and River Wey CEs, having a degree was found to reduce respondents marginal utilities of income but, counter intuitively, in the national CE having a higher income actually increased it. Similar results were obtained from analyzing the pooled data. These results indicate that socioeconomic variables only influenced preferences towards the cost attribute, with the effect of income being contrary to conventional assumptions when considering between catchment populations. This reflects similar observations by (Hanley et al., 2006b; Johnston and Rosenberger, 2010). Consequently, socioeconomic factors are unlikely to systematically and successfully explain variation in WTP and correct benefits transfer error in the context of river barrier mitigation. Furthermore, as the socioeconomic variables appear to only significantly influence preferences for the cost attribute, they should only be used to adjust for population effects in benefit function transfers when environmental improvements are to be funded via a local payment vehicle.

As expected, having a pro-ecological attitude was associated with a higher marginal utility for the Tot_Fish attribute in the national sample. For the pooled sample, a pro-ecological attitude was associated with higher marginal utilities for both the Var_Wild and Tot_Fish attributes. For the national and pooled samples, having a pro-ecological attitude reduced respondents marginal utilities of income, although this may reflect these respondents were less attentive to the cost attribute. These results indicate environmental attitude is a more consistent predictor of attribute preferences than the selected socioeconomic variables, particularly in the larger pooled dataset and across catchment populations in the national sample.

Analysis of the pooled data also revealed that respondents from the River Wey sample had significantly smaller marginal utilities for the Tot_Fish attribute. No significant differences in scale (i.e., differences in the unobserved influences on choices in the two CE sample groups) were identified across the two datasets, confirming the River Wey respondents had genuinely different taste preferences for the Tot_Fish attribute. Once scale was controlled for between and within sample groups, preferences for the Var_Wild attribute were found to be homogeneous for the pooled sample. This suggests that taste preferences for the Var_Wild attribute are generally homogenous between and within catchments. This is believed to be due to the attribute being linked to personally consumable ecosystem goods, such as iconic species viewing or altruistic preferences for increased wild species diversity. The Tot_Fish attribute was more closely linked to ecosystem goods that support local community benefits, such as local tourism opportunities and recreational benefits for others. Consequently, attributes that capture more community orientated benefits will be less robust to transfer due to variations in social norms for supporting local opportunities and recreational pursuits within different benefiting populations.

The G-MNL-II model identified significant scale heterogeneity across individuals in the pooled dataset. However, accounting for scale did not appear to significantly change implicit prices (IPs) for the ecological attributes. This reflects findings elsewhere in the literature (e.g., Hensher, 2012). Nonetheless, scale differences appear to be significant with respect to preferences to depart from the status quo.

In general, the literature is reasonably supportive of the transfer of IPs between study and policy sites. Using a utility specification that omits all observed data on respondents (RPL Model 1), the following generic IPs for local rivers are estimated using results from the national CE:[9]

- Var_Wild = £2.75 per year per household (hh) for five years (Total £13.75).
- Tot_Fish = £0.18 per year per household for five years (Total £0.90)

Evaluating a novel form of benefit transfer, the above generic IP estimates are compared with those estimated from the parallel CE at the River Wey. Equivalence testing confirmed the generic IP for Var_Wild to be robust to transfer from the national generic context to the named local catchment case study ($<$ 20% transfer error). The generic Tot_Fish IP was found to be less robust, although the River Wey IP was still found to be within 75% of the generic IP at the 95% confidence

[9] As reported in Table 4.9.

level. These findings are as expected given the significant differences in marginal utility for the Tot_Fish attribute between the two sample groups.

Differences in compensating surplus for different policy packages are not investigated as the alternative specific constants were significantly more negative in the River Wey choice experiment. The local stewardship motivations speculated to be driving the differences in ASCs are likely to vary significantly between catchments. As such, it is believed that full benefits function transfer between catchments will suffer significant transfer error due to the effect of ASCs on compensation surplus estimations, at least in the context of river barrier mitigation. Indeed, the literature review in Section 2.6 suggests equivalence of compensating surpluses is only obtained for benefit transfer studies involving very similar study and policy sites and benefiting populations. As such, Morrison et al. (2002) suggestion that it is prudent to rely solely on IPs when catchments differ in unobservable aspects is followed. It is noted that the ASC was negative and significant in both samples, thus relying on IPs results in a conservative underestimate of the welfare benefits of barrier mitigation action. Accordingly, the welfare effect of implementing a barrier mitigation program that increased average fish species by 2 and total fish number by 5 per 120m length of river can be estimated to be £32.40/hh.[10] In so saying, it is acknowledged that benefit estimates for policy packages that focus on fish species richness increases will be much more robust than those focusing on total fish number increases.

The results presented are believed to be of direct relevance to policy makers and watershed managers involved in river barrier mitigation actions designed to meet the requirements of the WFD. The generic IPs presented are suited to small to medium sized local catchments similar to the River Wey where there is unlikely to be funding for original studies but CBA of river barrier mitigation action is still required. Given the robustness of the Var_Wild IP, consideration could be given to calculating welfare benefits solely on the basis of the increased provision of this attribute to ensure that the benefits of barrier mitigation are not over estimated at a policy site. This should also be the case if the policy objectives are purely ecological and / or the public amenity benefits accruing from fishing rights are restricted. This is likely to be the case for benefits accruing from barrier mitigation programs implemented in response to policies such as the endangered species act in the US and the habitats directive in the EU. For rivers that differ substantially in characteristics from the River Wey (e.g., large rivers with big benefit populations), original estimates of the benefits of river barrier mitigation may be required.

[10] Based on ((2 x £2.75 per fish species) + (5 x £0.18 per total fish)) x 5 years.

5. How to Choose? Economic Valuation and Optimal Planning of River Barrier Mitigation Actions

5.1. Abstract

Infrastructure, such as dams, weirs and culverts, disrupt the longitudinal connectivity of rivers, causing adverse impacts on fish and other species. This compromises the ability of river ecosystems to provide a range of services that contribute to human well-being. Improving fish passage at artificial barriers is an economic river restoration policy option that can improve the delivery of river ecosystem services provision. Whilst a number of methodologies exist to cost-effectively prioritize barriers for mitigation action, there is also now considerable interest in estimating the economic benefits of increased ecosystem service provision from investing in this activity. This is relevant in a number of policy contexts, including the Water Framework Directive in the EU. In this chapter the techniques and results from Chapters 3 and 4 are combined in a novel bio-economic model that addresses the dual problem of prescribing cost optimal river barrier mitigation solutions whilst, simultaneously, estimating the social benefit of undertaking this activity. The specific advantage of this approach is it can readily inform cost benefit analysis of river barrier mitigation policy. The methods are demonstrated using the River Wey in South East England, containing over 650 artificial barriers, as a case study. For the case study, the benefits of investing in river barrier mitigation exceed costs at all budget levels, with the most socially efficient level of investment identified as approximately £30M.

5.2. Introduction

Improving river connectivity via the removal of fish passage barriers has been demonstrated to deliver increased fish density (Gardner et al., 2013), diversity (Catalano et al., 2007) and rapid colonization of stream reaches (Roni et al., 2008). As such, river barrier mitigation is identified as one of the most effective means of improving fish populations at the catchment scale (Roni et al., 2002; American Rivers et al., 1999). In recognition of the adverse effects of artificial barriers on river ecosystems a number of legislative drivers for improving longitudinal connectivity now exist. For example, the Water Framework Directive (WFD) in the EU obliges member states to improve fish passage at artificial barriers (Kemp et al., 2008). This is also highlighted as an essential activity in achieving regulatory requirements under the EU Eel Recovery Plan (Piper et al., 2013). In the US, river barriers are highlighted for mitigation action under environmental statutes such as the Endangered Species Act (Pohl, 2002). In light of these legal imperatives, environmental agencies are seeking methodologies that can cost-effectively prioritize river barriers for mitigation to maximize ecological returns with expenditure. At the same time, there is also considerable interest amongst policy makers and river managers in estimating the economic benefits of investing in this activity (EA, pers. com; SEPA, pers. com).[1] This information can facilitate cost benefits analysis (CBA), which is now routinely carried out by many government bodies when formulating and administering environmental policy (Johnston and Rosenberger, 2010). This can assist in developing effective policy responses to the problem of river fragmentation at national, regional and catchment scales. For instance, the WFD specifically requires CBA in catchment management plans in order to direct an efficient allocation of economic resources to the problems of environmental protection (Hanley et al., 2006b; Del Saz-Salazar et al., 2009).

In this chapter, an integrated framework that simultaneously addresses the dual problem of prescribing cost optimal river barrier mitigation solutions for resident fish and estimating the social economic benefit of pursuing this activity is presented. The overarching purpose of this framework is to inform CBA of policies to improve river connectivity via barrier mitigation action. In order to achieve this aim, two lines of research are drawn together, namely: 1) estimating the benefits of river barrier mitigation using non-market valuation techniques (presented in Chapter 4); and, 2) maximizing river habitat connectivity and predicted gains in resident fish species richness within an optimization modeling framework (presented in Chapter 3).

In order to inform the benefits estimation, the ecosystem services approach to environmental valuation is adopted (Bateman et al., 2011). This allows identification of the ecosystem services (goods) contributing to human well-being whose provision is improved via river barrier mitigation. This then provides a list of ecosystem goods on which the non-market valuation can focus, which is undertaken using the Choice Experiment (CE) method. These improved ecosystem services are explicitly linked to the biophysical attributes of fish species richness and abundance. As such the CE method is particularly useful as it reveals marginal willingness to pay (implicit prices) for improvements in the underlying biophysical ecological inputs to ecosystem services. This work is described in full in Chapter 4.

[1]Letters of support in this regard have been provided by both the Environment Agency for England & Wales and the Scottish Environmental Protection Agency

In order to to generate cost optimal solutions to the river barrier mitigation problem, an extension of the Resident Fish Passage Barrier Removal Problem (R-FPBRP) presented by O'Hanley et al. (2013b) is employed. The R-FPBRP maximizes longitudinal connectivity for resident fish species. Chapter 3 describes how this model can be can be developed to provide estimates of average fish species gains using fish population survey data and standard statistical approaches (R-FPBRP(S) model). In this chapter, it is shown how the implicit prices estimated from the CE reported in Chapter 4, can further be incorporated into the R-FPBRP(S) (the R-FPBRP(V) model).

The R-FPBRP(V) model provides an integrated framework for simultaneously generating cost optimal river barrier mitigation solutions, whilst estimating the social economic benefit arising from their application. Whilst a number of optimization models for solving river barrier problem exist in the literature, the R-FPBRP(V) contributes to this by providing a novel approach that maximizes social economic benefit as the objective. As the framework can readily facilitate CBA of river barrier mitigation at the catchment scale, it is anticipated to be of direct use to practitioners and policy makers involved in river management.

The remainder of the chapter is organized as follows. In Section 5.3, the CE method is briefly summarized. In Section 5.4 the optimization models are presented. Section 5.5 demonstrates the methods and presents an economic analysis of the policy of river barrier mitigation for the River Wey case study. Section 5.6 provides concluding remarks.

5.3. Choice Experiment

The Choice Experiment (CE) technique is employed in order to undertake the economic analysis. The full details of the CE are presented in Chapter 4, a brief summary of the approach employed is provided here for the sake of clarity and convenience. In a CE respondents are asked to choose between different consumption bundles of ecosystem goods / services that are characterized by the levels of certain attributes they possess, one being the cost for provision. In the analysis presented in Chapter 4 a 'pragmatic' ecosystem services approach is adopted. Under this approach respondents are informed of the ecosystem goods whose provision will improve as a result of increasing the biophysical attributes of fish species richness and fish abundance offered in the CE. Council tax is adopted for the cost attribute.

The technique is based upon Lancaster's characteristics theory of goods, with the associated choice models underpinned by random utility theory (Hanley et al., 1998b). The probability a respondent q chooses any given bundle i over all others $j \neq i$ is the probability that its utility is greater (i.e., $U_i > U_{j \neq i}$). Under the random utility framework, U is composed of a deterministic component V (characterized by the k number CE attributes) and a random unobservable component ε (Manski, 1977).

Consequently, the utility function for respondent q choosing from a bundle of j different alternatives takes the form:

$$U_{jq} = ASC_j + \sum_k \beta_k X_{kj} + \varepsilon_{jq} \tag{5.1}$$

where ASC_j is an alternative specific constant for bundle j, X_{kj} the k^{th} attribute value in bundle j and β_k the associated coefficient. Given a sufficient number of observations, probabilistic choice models can then be employed to recover the β_k values in equation (5.1)(Colombo and Hanley, 2008). From these average values for the marginal utilities in equation (5.1) can be calculated. The marginal willingness to pay for a unit increase in any non-monetary attribute (implicit price, IP) can then be recovered using the following relationship:

$$IP_K = -\beta_K/\beta_c \tag{5.2}$$

Where, β_K is the marginal utility of the K^{th} non monetary attribute (e.g., fish species richness) and β_c the marginal utility of the cost attribute. As Morrison et al. (2002) observe IPs are useful for decision makers as it allows the benefits of different levels of environmental quality to be estimated. As such they readily lend themselves to integration in optimization modeling frameworks.

5.4. Optimization Model

As highlighted in Chapters 2 and 3, optimization methodologies provide a *scalable* method of exploring all possible combinations of barrier mitigation actions so that the optimal solution that maximizes river restoration gains given available resources can be identified. These optimization approaches model rivers as dendritic ecological networks (DENs), where the river network is characterized by a branching structure with branches forming as one moves in the upstream direction. The model then seeks to maximize an objective (say accessible habitat) via a set of decision variables but subject to a set of constraints, normally including budget. Habitat accessibility for fish (aka, longitudinal connectivity) within a river system is determined not only by the the relative positions all the barriers within the catchment but also their passabilities (Diebel et al., 2014). Given the interest in habitat fragmentation in rivers, a number of connectivity metrics have been proposed in order to assess the impact of barriers on longitudinal connectivity. As noted in Chapter 3, connectivity metrics (e.g., those presented by Cote et al. (2009); McKay et al. (2013); Diebel et al. (2014)) are useful benchmarks for assessing barrier mitigation strategies as the relative benefit of mitigating given barriers within river systems can be evaluated by examining the effect on these metrics. The R-FPBRP(S) developed in Chapter 3 provides such an approach for determining the optimal subset of barriers to target for mitigation action given budgetary constraints. This model was developed from the non-linear R-FPBRP presented by O'Hanley et al. (2013b), which employs the C metric to maximize habitat accessibility for resident fish. This non-linear approach is summarized below. The non-linear model is presented at this stage as it simplifies the presentation of the models that incorporate economic data in the latter sections (i.e., the R-FPBRP(V) and R-FPBRP(Vopt)). In the practical application of these models the R-FPBRP(V) and R-FPBRP(Vopt) can be readily adapted form the linear version of the R-FPBRP(S) presented in Chapter 3.

5.4.1. The *C* Metric

The C metric was shown to be statistically significant in explaining fish species richness in Chapter 3. For the sake of clarity and convenience its construction is repeated here. Using the notation provided in Table 5.1, the C Metric is constructed by first calculating the total availability A_{sh} of habitat type h accessible from a given river subnetwork s, as follows:

$$A_{sh} = \sum_{t \in S} D_{st} v_{th} z_{st} \tag{5.3}$$

In equation (5.3) the amount of habitat type h in subnetwork t that can be accessed from subnetwork s (v_{th}) is adjusted by both the distance between the two subnetworks (via D_{st}) and the compound probability of a fish successfully negotiating all the intervening barriers on the journey from s to t and back again (z_{st}). z_{st} assumes each barrier is independent and is simply the product of the bidirectional passability of each barrier. The habitat available within subnetwork s is also included in the calculation of A_{sh}, where there is no intervening distance or barriers for this journey (i.e., $D_{ss} = z_{ss} = 1$).

The baseline availability A^0_{sh} of habitat type h accessible from subnetwork s assuming no artificial or natural barriers exist in the river network is defined as:

$$A^0_{sh} = \sum_{t \in S} D_{st} v_{th} \tag{5.4}$$

The D_{st} term employed in the calculation of A_{sh} and A^0_{sh} represents a distance weighted dispersal factor for the journey between subnetworks s and t. Diebel et al. (2014) define D_{st} as an inverse function of both the absolute distance between subnetworks s and t (d_{st}) and the dispersal ability of the fish species / guild considered (d'), such that:

$$D_{st} = \frac{1}{1 + \left(\frac{d_{st}}{d'}\right)^2} \tag{5.5}$$

Thus, the current connectivity (C metric) for a given inter-barrier river subnetwork

C_s^0 can be calculated as follows:

$$C_s^0 = \frac{1}{m} \sum_{h=1}^{m} \frac{A_{sh}}{A_{sh}^0} \tag{5.6}$$

Table 5.1.: Notation used in C metric.

Symbol	Definition
S	Set of all inter-barrier river subnetworks, indexed by s and t
H	Set of habitat types within the catchment, indexed over h with cardinality m
v_{th}	Total amount of habitat type h in subnetwork t
z_{st}	The product of the bidirectional passabilities of all barriers traversed when traveling from subnetwork s to subnetwork t and back again
d_{st}	Distance for route between subnetworks s and t
d'	Dispersal distance of focal fish species / guild considered

5.4.2. The Resident Fish Passage Barrier Removal Problem (R-FPBRP)

The R-FPBRP determines the set of barriers to mitigate in order to maximize connectivity weighted habitat for resident fish, subject to budget. The linear formulation of the model is provided in Chapter 3. In order to formulate the non-linear R-FPBRP, the notation introduced in Table 5.1, the additional notation provided in Table 5.2 and the following binary decision variable are employed:

$$x_{ji} = \begin{cases} 1 & \text{if mitigation project } i \text{is carried out at artifical barrier } j \\ 0 & \text{otherwise} \end{cases}$$

A nonlinear formulation for R-FPBRP is then given as follows:

$$\text{R} - \text{FPBRP} \ \max \sum_{s \in S} v_s C_s \tag{5.7}$$

s.t. :

$$z_{st} = \prod_{j \in B_{st}} \left(p_j^0 + \sum_{i \in E_l} p_{ji} x_{ji} \right) \qquad \forall (s,\, t) \in S,\ s \neq t \tag{5.8}$$

$$z_{st} = z_{ts} \qquad \forall (s,\, t) \in S,\ s \neq t \tag{5.9}$$

$$z_{ss} = 1 \qquad \forall s \in S \tag{5.10}$$

$$A_{sh} = \sum_{t \in S} D_{st} v_{th} z_{st} \qquad \forall s \in S,\ h \in H \tag{5.11}$$

$$C_s = \frac{1}{m} \sum_{h=1}^{m} \frac{A_{sh}}{A_{sh}^0} \qquad \forall s \in S \tag{5.12}$$

$$\sum_{i \in E_j} x_{ji} \leq 1 \qquad \forall j \in J^* \tag{5.13}$$

$$\sum_{j \in J^*} \sum_{i \in E_j} c_{ji} x_{ji} \leq b \tag{5.14}$$

$$x_{ji} \in \{0, 1\} \qquad \forall j \in J^*, i \in E_j \tag{5.15}$$

The objective (5.7) calculates the sum of connectivity weighted habitat $v_s C_s$ across every inter-barrier subnetwork s within the river system. Equations (5.8) determine the bidirectional passability for every possible inter-subnetwork journey (z_{st}). z_{st} is the product of the initial bidirectional passability (p_j^0) plus any improvements in passability (p_{ji}) from mitigation action undertaken (i.e. $x_{ji} = 1$) at all the intervening barriers on the route between subnetworks s and t (i.e., all barriers in the set B_{st}). z_{st}, therefore, represents the cumulative probability that a fish is able to make the journey from subnetwork s to t and back again. Equations (5.9) represent a symmetry assumption and ensure the cumulative passability is the same in either direction. Equations (5.10) ensures that the probability of being able to access the habitat within subnetwork s is 1. Equations (5.11) determine the amount of habitat type h accessible from a given subnetwork s (A_{sh}) and equations (5.12) the C metric for that subnetwork (C_s) following any mitigation actions undertaken (introduced previously as equations (5.3) and (5.6), respectively). Constraints (5.13) ensure only

Table 5.2.: Notation used in R-FPBRP.

Symbol	Definition
S	Set of inter barrier river subnetworks, indexed by s and t
J	Set of all artificial and natural barriers, indexed by j
J^*	Set of barriers for which at least one mitigation project exists (i.e., $\lvert E_j \rvert \geq 0$) indexed by j
E_j	Set of mitigation projects available at barrier j, indexed by i
B_{st}	Set of intervening barriers between subnetworks s and t, indexed by j
v_s	Amount of habitat in subnetwork s (e.g., river length, watershed area)
p_j^0	Initial bidirectional passability of barrier j
p_{ij}	Increase in bidirectional passability at barrier j given implementation of mitigation project i
c_{ij}	Cost of implementing mitigation project i at barrier j
b	Available budget for carrying out mitigation actions

one mitigation project i can be carried out at any given barrier. Inequality (5.14) stipulates that the total cost of barrier mitigation actions cannot exceed the total available budget b. Constraints (5.15) impose binary restrictions on the x_{ji} decision variables.[2]

5.4.3. R-FPBRP(S) For Estimating Average Fish Species Gain

As identified in Chapter 3, where sufficient fish survey data exists the relationship between a subnetworks current C metric value (C_s^0) and fish species richness (R_s) can be empirically estimated using statistical techniques. The R-FPBRP can then, in turn, be modified so as to maximize gains in average fish species richness. The linear version of this revised R-FPBRP(S) model is presented in Chapter 3. In order to formulate an equivalent non-linear R-FPBRP(S), the following additional variables are introduced:

V = Total amount of habitat within the river system

β_1 = regression coefficeint on $C_s^0$for estimating R_s

$\triangle C_s$ = change in connectivity of subnetwork $s$following mitigation actions

The R-FPBRP(S) model is given by replacing the objective (5.7) with the new

[2]It should be noted that z_{st} in equation (5.8) is a polynomial and, therefore, introduces non-linearity into the R-FPBRP, making this optimization model hard to solve. The linear reformulation of the R-FPBRP that can be solved using off-the-shelf optimization software solvers like CPLEX and GUROBI is provided in Chapter 3.

objective function (5.16) and adding equations (5.17):

$$\mathrm{R-FPBRP(S)}\ \max \frac{1}{V}\sum_{s\in S} \triangle C_s\,\beta_1\,v_s \tag{5.16}$$

s.t. equations (5.8) – (5.15) and the following:

$$\triangle C_s = C_s - C_s^0 \tag{5.17}$$

The R-FPBRP(S) objective (5.16) now maximizes the habitat weighted average net species gain across all subnetworks in the river system following barrier mitigation.

5.4.4. R-FPBRP(V) Bio-Economic Optimization Model

The social benefit value of implementing a barrier mitigation program can be estimated by multiplying the net species gain maximized in the R-FPBRP(S) model by an implicit price for fish species richness (IP) and the size of the relevant benefiting population (N). This is referred as the R-FPBRP(V) model, where the R-FPBRP(S) objective is extended as follows:

$$\mathrm{R-FPBRP(V)}\ \max\ IP\ N\ \frac{1}{V}\sum_{s\in S} \triangle C_s\,\beta_1\,v_s \tag{5.18}$$

s.t. equations (5.8) – (5.15) & (5.17)

A particular attraction of the R-FPBRP(V) model is that it allows the different budget costs of river barrier mitigation solutions to be directly compared against the estimated benefits of their implementation. The model can also be modified to determine the socially optimal level of investment in river barrier mitigation action. This is referred to as the R-FPBRP(Vopt) model, where the R-FPBRP(V) model is reformulated as follows:

$$\mathrm{R-FPBRP(Vopt)}\ \max\ \underbrace{\left(IP\ N\ \frac{1}{V}\sum_{s\in S} \triangle C_s\,\beta_1\,v_s\right)}_{(i)} - \underbrace{\sum_{j\in J^*}\sum_{i\in E_j} c_{ji}x_{ji}}_{(ii)} \tag{5.19}$$

s.t. equations (5.8) – (5.13), (5.15) & (5.17)

The objective function (5.19) maximizes the total net benefit value of river barrier mitigation actions. The first part (5.19(i)) calculates the value of the benefits delivered from implementing the socially optimal river barrier mitigation solution, whilst the second part (5.19(ii)) captures the one-off cost of implementing this solution.

Given that the objective (5.19) maximizes the difference between benefits and costs, the budgetary constraint (5.14) is dropped from the model.

The model assumes that the IP captures the full net present value of the river barrier mitigation benefits delivered over the policy planning horizon. Where willingness to pay (WTP) for increased fish species richness is estimated on a per year, or other periodic basis, this can be readily estimated using established discounting procedures (e.g., Willis and Garrod, 1999; Pearce et al., 2006). If increases in fish species richness have additional valuable benefits (e.g., to total fish production) these can also be included directly in the IP in (5.16), provided the value of the contribution of fish species richness to the underlying ecological production function can be isolated and determined. Alternatively, the objective (5.16) can be extended by directly including other welfare benefit measures that arise as a function of connectivity improvements. This is accomplished in the same fashion as including the welfare measures for the fish species richness improvements. However, it should be noted that any such approach requires the determination of a statistically significant causal relationship between connectivity and additional river ecosystem good(s) (or proxy for goods) and associated marginal measures of welfare for the provision of these good(s). For example, it may be possible to estimate a regression coefficient (β_a) for fish abundance responses to increases in connectivity (ΔC_s) via statistical analysis. A marginal measure of welfare for fish abundance (IP_a) was derived in Chapter 4. Accordingly, the benefit of fish abundance responses to river barrier mitigation could readily be incorporated into the objective for the R-FPBRP(V) as follows:

$$\mathrm{R-FPBRP(V)}\ \max\ \left(IP\ N\ \left(\frac{1}{V}\sum_{s\in S}\triangle C_s\,\beta_1\,v_s\right)\right)+\left(IP_a\ N\ \left(\frac{1}{V}\sum_{s\in S}\triangle C_s\,\beta_a\,v_s\right)\right)$$

5.5. River Wey Case Study

5.5.1. Background

The River Wey is a tributary to the River Thames and is located in the South East of England, as shown in Figure 5.1. The EA Fisheries Action Plan for the Wey Valley identifies the presence of physical obstructions as a key pressure on fish species richness and abundance (EA, 2009). An inventory of these obstructions has been completed by the University of Southampton (as described in Chapter 3). As part of their ongoing monitoring the EA have also completed 145 fish surveys within the River Wey catchment between October 1989 and October 2011. Angling is widespread and established in the River Wey catchment, with 30 different local angling clubs and organizations consulted during the development of the EA Fisheries Action Plan. I undertook extensive inspections across the catchment during weekend periods in the Summer of 2010. This revealed that angling clubs hold private fishing rights to a large majority of the accessible reaches of the River Wey.

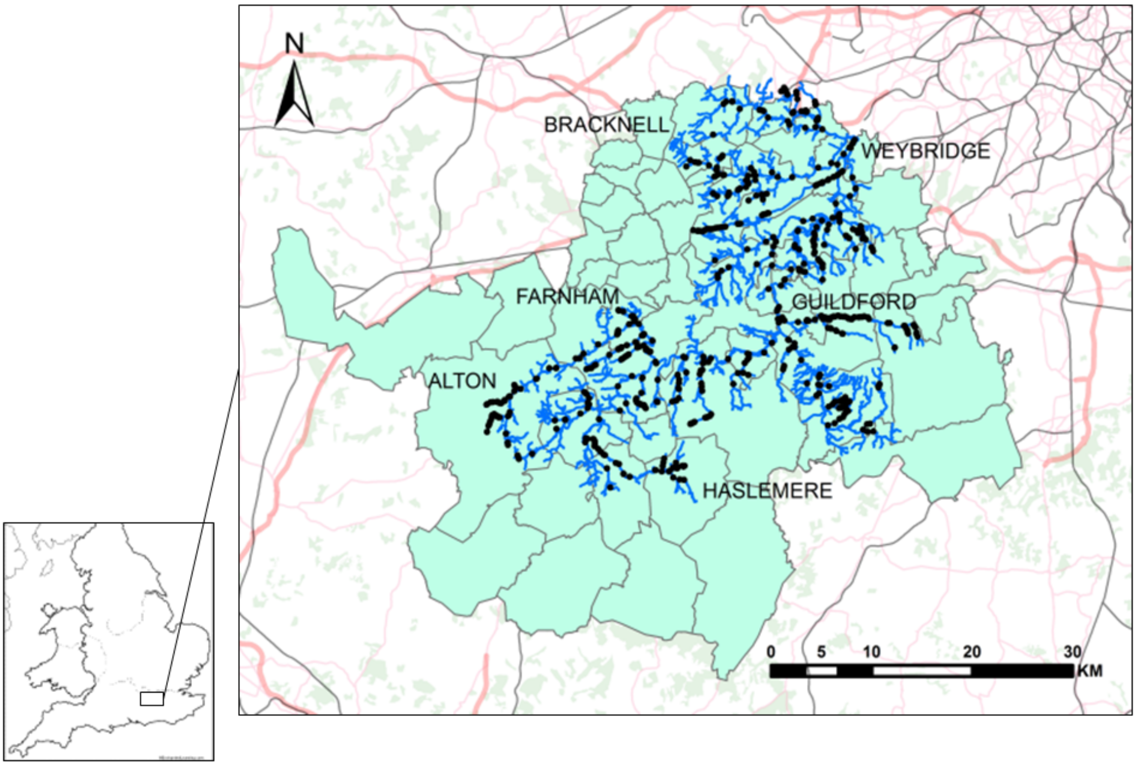


Figure 5.1.: Location and extent of River Wey catchment. Barriers are represented by small dots. Blue shaded areas represent the postcode boundaries for the benefiting population.

A full description of the River Wey catchment is provided in Chapters 3 and 4. The findings from these chapters are used to parametrize the R-FPBRP(S), R-FPBRP(V) and R-FPBRP(Vopt) models presented herein. For the sake of convenience the estimation of these relevant parameters is summarized below.

5.5.2. Statistical Analysis of Fish Survey Data

In order to parametrize the R-FPBRP(S) model it is necessary to estimate the magnitude and confirm the significance of the effect of the C metric (C) on species richness. In order to do so the following statistical model is employed to analyze the EA fish survey data for the River Wey (as proposed in Chapter 3):

$$R_s = \beta_0 + \beta_1 C_s^0 + \beta_2 \sqrt{USL_s} + \sum_{t=1}^{T} \beta_{2+t} dummy_t + \mu \tag{5.20}$$

Where R_s is the species count observed during a survey event, C_s^0 is the current C metric value for the subnetwork in which the survey event occurred, $\sqrt{USL_s}$ the square root of the total length of habitat upstream of s (a proxy for stream size), β_0

is a constant and $dummy_t$, $t = 1 \dots T$, are a series of dummy variables for the year the fish surveys were undertaken with associated parameters β_{2+t} and are included to control for within year effects. β_1 and β_2 are the parameter estimates of particular interest and μ is an error term. Given the dependent variable (R_s) is characterized as a non-negative integer, a generalized Poisson regression count data model that can accommodate underdispersion of the data is employed.

The statistical model in equation (5.20) was estimated using the LIMDEP version 10 software package (Econometric Software, 2012), the results are summarized in Table 5.3. The year dummy variables are omitted from the table as their inclusion was purely to control for temporal variation. The parameter estimates for C and for $\sqrt{USL}$ are significant at the 95% and 99% confidence levels respectively. These parameter estimates describe the effect of a one unit increase in C or $\sqrt{USL}$ on $\ln R$. Direct marginal effects can be calculated for C and $\sqrt{USL}$ by evaluating the effect of these variables on the expected value of R when computed at the means of the sample data. These results are reported in the final ($^{dy}/_{dx}$) column in Table 5.3. The direct marginal effect for $\sqrt{USL}$ remains significant at the 99% level. The marginal effect of 15.43 for C is significant at the 95% confidence level. Given this reflects the linear relationship between R and C, this is the value the parameter estimate β_1 takes in the objective (5.16) of the R-FPBRP(S) model.

Table 5.3.: Results of Fish Species Richness Statistical Analysis for the River Wey Dataset.

	Generalized Poisson	
	Coeff (s.e.)	dy/dx (s.e.)
α	1.54 (0.12)***	-
C	2.40 (1.14)**	15.43 (7.27)**
$\sqrt{USL}$	0.0007 (0.0001)***	0.0047 (0.0006)***
θ	-0.044 (0.008)***	
R^2	-	
$pseudo - R^2$	0.042	
AIC	520.9	

*** P ≤0.01, ** P ≤0.05.

5.5.3. Choice Experiment

The CE was administered to a panel of online respondents residing at postcodes within approximately 10km of a River Wey watercourse by a market research company. The areas covered by these postcodes are shaded blue in Figure 5.1. This resulted in a 206 useable survey responses being obtained. Each respondent completed 6 choice tasks, representing 1,236 (206 x 6) choice observations for use in estimating the probabilistic choice model. A copy of the survey instrument employed is presented in Appendix D.

In order to parametrize the R-FPBRP(V) model it is necessary to estimate IPs for fish species richness. To achieve this marginal utilities for the CE attributes (β's) were estimated for respondents deterministic utility function (5.1), using the RPL Model 1 presented in Chapter 4. The RPL Model 1 parameters were estimated using the NLOGIT version 5 software package (Econometric Software, 2012). IPs for the CE attributes were then recovered using equation (5.2). The IPs for fish species richness and fish abundance are presented in Table 5.4, which reveals significant WTP for both of these attributes.

It should be noted that a significant negative ASC was encountered, implying that respondents are WTP for river barrier mitigation for reasons other than improving fish populations. As such the IPs presented reflect conservative estimates of respondents overall stated WTP for river barrier mitigation programs. A full discussion of the CE results is presented in Chapter 4.

Table 5.4.: IPs for fish attributes.

CE	Fish species richness		Total Fish Abundance	
	IP (s.e.)	IP (5 Year)	IP (s.e.)	IP (5 Year)
River Wey	£2.38 (0.29)***	£11.90	£0.09 (0.02)***	£0.45

*** P $\leq$0.01

5.5.4. Optimization Models

5.5.4.1. Dataset

Whilst detailed previously in Chapter 3, a full description of the River Wey dataset and the additional parameters to inform the R-FPBRP(V) and R-FPBRP(Vopt) models, is provided below for convenience.

The location of each barrier identified during the inventorying undertaken within the River Wey catchment was matched to the EA's detailed river network (DRN) hydrological plan using expert GIS techniques by the University of Southampton. The University of Southampton completed assessments of passability for a subset of 129 of these barriers. For barriers whose passability had not been assessed, this was inferred from similar barriers elsewhere in the catchment for which passability had been determined. For the purposes of the analysis presented, passabilities commensurate with adult trout were adopted. The amount of habitat above any given barrier is characterized as the summed river lengths between that barrier and its immediate upstream barriers or the terminal points of the hydrological plan. Only a single habitat type is considered for the catchment as over 75% of the river stretches on the DRN are classified as primary river. A dispersal distance for fish is generically assumed to be 12.5km (based on sensitivity analysis). The final dataset employed in the analysis comprises of 1,160km of watercourses with 650 different candidate barriers for mitigation action.

A single mitigation project is considered for each candidate barrier. Barriers outside of the middle and lower stretches of the main river channel and navigation sections were considered suitable candidates for complete removal, thereby restoring full passability in both directions (i.e. $p_j^0 + p_{ij} = 1.0$). Barriers associated with the middle and lower stretches of the main river channel and navigation sections were not considered suitable for removal due to the associated effects on water level and navigation in this part of the river system. These barriers were considered candidates for provision of fish passes that increased upstream passability to 0.75 and restored full passability in the downstream direction (i.e. $p_j^0 + p_{ij} = 0.75$), generally reflecting the findings of Noonan et al. (2012). For the purpose of the analysis it was assumed that bidirectional passability at locks could be increased to 0.65 via investments in more regular and improved operations. The costs of barrier mitigation were estimated on the basis of information provided by the River Restoration Council for works at similar structures (pers. coms.) and information published by the EA (EA, 2010). Based on these costs, the total budget required to mitigate all 650 candidate barriers within the River Wey system was calculated as £53,355,000, or approximately £55 million. In order to parametrize the R-FPBRP(S) model it is necessary to specify a fish species richness : connectivity response parameter. The linear co-efficient for C (β_1) presented in Table 5.3 (15.43) is employed in this regard.

In order to parametrize the R-FPBRP(V) bio-economic model it is necessary to specify an appropriate IP and benefiting population size (N). In this regard, the IP for fish species richness of £11.90 for the River Wey, presented in Table 5.4, is employed.[3] It should be noted the IP adopted represents an instantaneous estimate of total benefit value, rather than a flow overtime, hence, there is no need to consider a policy planning horizon and discount rate or estimate the net present value. The benefit value from increases in fish abundance resulting from barrier mitigation activity are omitted. This is due to the improvements in the fish abundance attribute being linked to ecosystem services related to recreational fishing opportunities (as detailed in Chapter 4). Given the noted the absence of public fishing rights in the accessible reaches of the catchment, it is considered inappropriate to include these benefits as they will not publicly accrue. Whilst this implies a market value exists for these benefits, this is unlikely to be significant in the context of the relative benefiting populations involved.[4] In order to estimate a value for N, the postcodes whose boundaries are within approximately 10 Km of the River Wey catchment were identified, as shown by the blue shaded areas in Figure 5.1. Total populations for

[3] Chapter 4 presents a generic IP, believed to be suitable for use in alternative but similar catchment benefits estimations.

[4] Only out of 7 out of 206 respondents to the CE survey indicated they participated in recreational fishing when visiting the River Wey. As such the total resident population is believed exceed that of recreational anglers at the River Wey by around two orders of magnitude.

these benefiting postcodes were determined from the 'All usual resident' counts for each postcode, as recorded in the 2011 UK national census, accessed via the Office for National Statistics NOMIS website (ONS, 2013). The total number of usual residents within the selected postcodes is 881,033 individuals. This was converted to an estimated 367,000 households using the national average of 2.4 persons per household (ONS, 2012).

5.5.4.2. Results

The linear version of the R-FPBRP(S) model presented in Chapter 3 was coded in OPL using CPLEX studio version 12.5 in order demonstrate its application on the River Wey dataset.[5] The results are presented in the second column of Table 5.5. The R-FPBRP(S) objective is in terms of maximum habitat weighted average net species gain. The results from the R-FPBRP(V) model are presented in the third column of Table 5.5. The R-FPBRP(V) objective is the value of the R-FPBRP(S) results, estimated using the IP for fish species richness from the River Wey CE (£11.90) and the estimated size of the associated benefiting population (367,000 households).

5.5.5. Policy Analysis

It is now possible to address the main objective of the research, is it economically rational to implement a river barrier mitigation policy in the River Wey catchment? Cost benefit analysis results in this regard are reported in the final two columns of Table 5.5. The first observation that can be made with respect to Table 5.5, is that the benefits of barrier mitigation action always exceed costs in the River Wey catchment (i.e., the benefit / cost ratio is always > 1). The benefits cost ratios presented also reveal generally decreasing returns on investment. However, this trend is not perfect given that the benefits cost ratio at the £15M budget (2.078) exceeds that at £10M (1.992). This indicates that thresholds for investment exist where benefit returns 'jump' up by a significant amount.

[5] All experiments were run on the same dual-core Toshiba Satellite Pro R850-15F laptop (Intel i3 processor, 2.10 GHz per chip) with 8 GB of RAM. The performance of the CPLEX implementation on the River Wey dataset is discussed in depth in Chapter 3.

Table 5.5.: Results of the R-FPBRP(S) and R-FPBRP(V) models on the River Wey dataset.

Budget (£M)	R-FPBRP(S) Objective (Species Gain)	R-FPBRP(V) Objective (Aggregate WTP £M)	Cost Benefits Analysis Benefit / Cost	Net Benefit (£M)
2.5	1.40	6.06	2.42	3.56
5.0	2.32	10.07	2.02	5.07
10.0	4.59	19.92	1.99	9.92
15.0	7.18	31.17	2.08	16.17
20.0	9.00	39.11	1.96	19.11
25.0	10.53	45.74	1.83	20.74
30.0	11.80	51.25	1.71	21.25
35.0	12.77	55.45	1.58	20.45
40.0	13.50	58.65	1.47	18.65
45.0	14.04	61.00	1.36	16.00
50.0	14.43	62.69	1.25	12.69
55.0	14.54	63.15	1.15	8.15

Table 5.5 also reveals that the overall net benefits of investing in river barrier mitigation generally increase at a decreasing rate, reaching a maximum of approximately £21.25M with an investment of £30M. This general pattern of diminishing returns with higher levels of investment reflects previous findings in the optimization literature (e.g., Kuby et al., 2005; O'Hanley and Tomberlin, 2005; Zheng et al., 2009; O'Hanley, 2011). This is clearly shown by the bell shape of the net benefits curve in Figure 5.2, where a maximum net benefit is reached at around the £30M budget level.[6] From an economic perspective this maximum reveals the socially optimal level of investment in river barrier mitigation, where marginal costs equal marginal benefits. Therefore, investments in river barrier mitigation above approximately £30M would not be supported on economic efficiency grounds.

The exact socially optimal level of investment in barrier mitigation in the River Wey system can be recovered using the R-FPBRP(Vopt) Model. This reveals the maximum possible net benefit of £21.27M is achieved with the socially optimal level of £30.32M of investment. Therefore, at the socially optimal level of investment, the benefits of river barrier mitigation action exceed costs by approximately 60%.

[6] It should be noted that this curve is not continuous but comprises of a series of step-wise increments at fine scale. This implies thresholds for investment exist in which a sufficient budget increase is required to make further connectivity improvements.

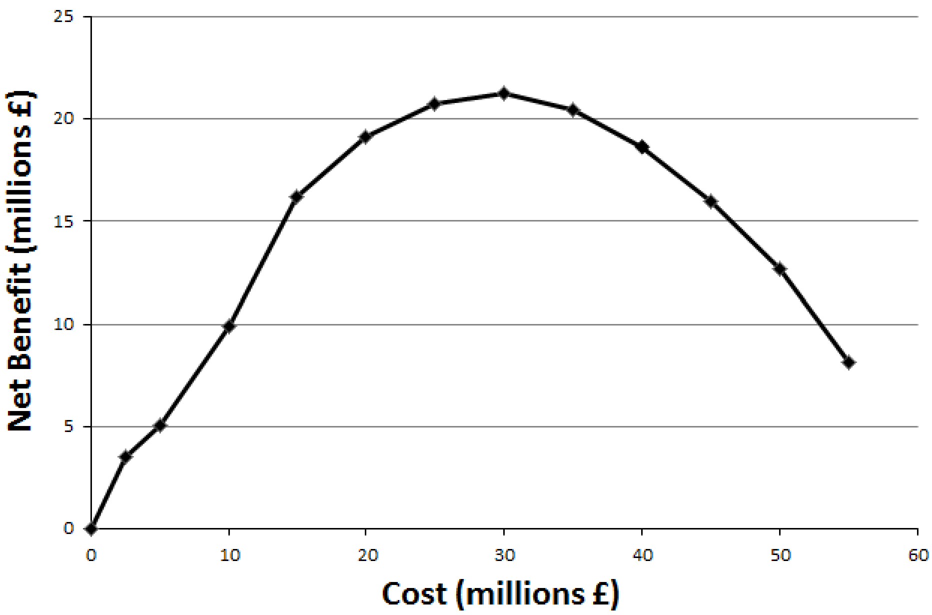


Figure 5.2.: Net benefit versus cost of undertaking river barrier mitigation.

As a final piece of analysis, sensitivity analysis of key parameters in the R-FPBRP(V) model using the result generated at the £30M budget (£51.25M) is undertaken. These key parameters comprise the values for the co-efficient on C (β_1), IP and N. Lower bound values for β_1 and IP are selected based on the values reported in Tables 5.3 and 5.4 respectively, minus a single standard error (LB1) and the associated $5^{\%ile}$ value (LB2). For the lower bounds for N, values of 75% of the households estimated using the postcode census data (LB1) and 50% of these households (LB2) are adopted. The results of the sensitivity analysis are presented in Table 5.6, which reveals the R-FPBRP(V) findings are sensitive to parameter estimate for C (β_1). Due to the large standard error for β_1 costs are found to exceed benefits (i.e., the benefit / cost ratio is < 1) at both LB1 and LB2 for this parameter, albeit only marginally for LB1. This reduces confidence in the assertion that river barrier mitigation is economically rational at all budget levels in the River Wey catchment. In so saying, uncertainty with respect to β_1 is expected given the use of an incomplete barrier dataset and a convenience survey for fish populations. The estimate for IP is reasonably robust, as such the benefit / cost ratio is > 1 for both LB1 and LB2. For N the benefit / cost ratio is > 1 at LB1 for this parameter but is $<$ 1 at LB2. However, given the size of the benefiting population has been estimated using census data, it is considered unlikely the actual value for this parameter will be substantially below LB1. As such it is considered unlikely that the potential variations in IP or N that could reasonably be anticipated would result in river barrier mitigation in the River Wey catchment not being supported on economic efficiency grounds for the £30M budget level.

Table 5.6.: Sensitivity analysis of key parameters in R-FPBRP(V) model based on results generated from the £30M budget solution (£51.25M).

Key Parameter	Value (S.E.)	Lower Bound		Revised Objective (WTP £M)	Benefit / Cost
β_1	15.43	LB1	8.16	27.10	0.90
	(7.27)	LB2	1.18	3.92	0.13
IP	£2.38	LB1	2.09	45.01	1.50
	(0.29)	LB2	1.81	38.98	1.30
N	367,000	LB1	275,250	38.43	1.28
	(-)	LB2	183,500	25.63	0.85

$5^{\%ile}$ values were calculated as the key parameter value minus (1.96 x s.e.).
'-' means no S.E. available.

5.6. Conclusions

There is increasing interest amongst river managers and policy makers in the removal or mitigation of river barriers to improve longitudinal connectivity and the delivery of ecosystem services in river systems. Economic analysis of the benefits ecosystem services provide is a key feature of the major ecosystem assessments that have been completed to date (Bateman et al., 2011). Furthermore, CBA of environmental policies to improve ecosystems and the environment in general is now routinely carried out by environmental agencies, for example under government rule making in the US and the Water Framework Directive (WFD) in the EU (Johnston and Rosenberger, 2010).

In this chapter a new framework for simultaneously cost optimally prioritizing barriers for mitigation action for resident fish species and estimating the social economic benefits of investing in this activity is presented (R-FPBRP(V) Model). This is achieved using a combination of choice experiments (CEs) and mixed integer linear programming (MILP). The R-FPBRP(Vopt) model presented can also be employed to promptly generate a river barrier mitigation solution that is, simultaneously, optimal with respect to cost and social economic efficiency. Embedding the optimization approach within a bio-economic model allows river barrier mitigation policy to be evaluated on the basis of both economic efficiency and cost optimality. This is believed to be crucial if the environmental goals of river barrier mitigation are not to be compromised in light of scarce public economic resources.

The approach is demonstrated using real data from the River Wey catchment in South East England. The framework consistently provided optimal river barrier mitigation solutions and estimated the social economic benefit value of their application for a full range of budget levels. The framework was also able to generate the solution corresponding to the socially optimal level of river barrier investment.

The cost benefit analysis (CBA) for the River Wey indicates that the benefits of implementing a policy of river barrier mitigation in the River Wey catchment exceed costs at all budget levels. The analysis also reveals the economically rational level of investment in barrier mitigation activity (i.e., where marginal costs equal marginal benefits) to be approximately £30M. At this socially optimal level of investment, the estimated benefits of river barrier mitigation action exceeded their cost by approximately 60%. The framework also benefits from the existence of a statistically robust generic IP for fish species richness improvements (as discussed in Chapter 4), thus rendering it transferable to other catchments of similar scope to the River Wey.

Given the current drivers for CBA of environmental policy, it is anticipated the framework presented will be of direct benefit to both policy makers and practitioners involved in river ecosystem management and barrier mitigation. Pareto optimal trade-off curves, such as Figure 5.2, can be constructed to identify levels of investment that deliver high social benefits at costs that can be justified in the policy context. Conversely, the trade-off curves and R-FPBRP(Vopt) model can also be used to demonstrate where the costs of implementing river barrier mitigation policy is excessive. This is important in order to direct an efficient allocation of economic resources to the problems of environmental protection. In this regard, the WFD specifically requires CBA in catchment management plans.

Whilst the case study example is considered to provide significant insight into river barrier mitigation issues in the River Wey, it is stressed that the analysis presented is meant for illustrative purposes only. Sensitivity analysis suggests the economic analysis is robust with respect to the potential variations in the IP and benefiting population values selected. However, doubt exists with respect to the species : connectivity response parameter (β_1 in equation (5.16)) given the nature of the barrier dataset employed and the use of a convenience fish survey sample. As such β_1 suffered large standard errors that, in turn, reduces the confidence in the CBA for the River Wey. There are a variety of reasons to expect uncertainty with respect to this parameter. For instance, the barrier inventorying undertaken was not supported by a full in-field survey of the River Wey catchment. Consequently, the barrier dataset may be incomplete. Furthermore, only approaching 20% of the barriers identified have been specifically characterized, with passabilities for the remainder of the barriers inferred from those of similar barrier types within the River Wey system. Finally, the passability assessment protocol employed has yet to be validated using actual fish passage data. In any real application the quality of the optimization model solutions would be much improved with the provision of a more comprehensive inventory of barrier passability and a fish population survey specifically designed to inform the analysis.

6. Conclusions and Further Work

6.1. Conclusions

The negative effects of multiple river barriers on both migratory and resident fish species alike is well documented. Consequently, improving fish passage at these barriers is considered to be one of the most cost-effective means of improving fish populations at the watershed scale (Roni et al., 2002).

In Chapter 2, a novel linear version of the Fish Passage Barrier Removal Problem (FPBRP) for optimizing barrier mitigation decisions for migratory fish is presented. Employing probability chains to evaluate cumulative passability results in a model that is highly efficient, scalable and can be readily implemented using off-the-shelf optimization software. For the case of migratory fish species, the case study analysis for watersheds in the US states of Washington and Maine confirms that substantial gains in habitat accessibility can be gained at low levels of investment. Thus, confirming barrier mitigation as a cost-effective river restoration option.

Chapter 3 presents a new linear formulation for the Resident - Fish Passage Barrier Removal Problem (R-FPBRP), which specifically considers habitat accessibility for resident fish species. An extension of the model is also presented (R-FPBRP(S)) that can be used in conjunction with standard statistical approaches to maximize predicted fish species richness gains. The case study analysis for the River Wey in South East England, confirms the reformulation of R-FPBRP to be more efficient and scalable than existing methods. The case study analysis reveals large and steady returns in fish species richness gains up to moderate investment levels. This indicates river barrier mitigation is indeed a cost-effective means of improving fish populations.

The ability to readily obtain prescriptive solutions that guarantee the most efficient use of limited resources highlights the advantage of optimization frameworks compared to other approaches, particularly when analyzing realistically sized datasets. It is believed that employing optimization models, such those present herein, is vitally important if river restoration goals are to be achieved in a cost-effective manner. To this end a clear description of the code and data file constructions to implement the FPBRP model is provided in Appendix A. It is hoped this will stimulate the use of optimization models amongst practitioners involved in river management.

Benefits analysis is a key feature of the major ecosystem assessments that have been completed to date. Furthermore, cost benefit analysis (CBA) of environmental policies to improve ecosystems and the environment in general is now routinely carried out by environmental agencies (Johnston and Rosenberger, 2010). Chapter 4 presents the findings of choice experiments (CE) to estimate the benefits of improvements in ecosystem service provision resulting from river barrier mitigation, specifically via increases in fish species richness and fish abundance. The CE is administered to national respondents and to respondents local to the River Wey. Both sample groups are found to have highly significant preferences for improving these attributes. For the national CE, Implicit Prices (IPs) of £13.75 for the species richness and £0.90 for the fish abundance attributes are estimated. For the River Wey CE, the estimated IP for the species richness attribute is £11.90 and for the fish abundance attribute it is £0.45. Evaluating a novel form of benefit transfer, the generic IP for species richness is found to be robust to transfer from the national generic context to the named local catchment case study (< 20% transfer error). These results are believed to be of direct use to practitioners involved in designing, evaluating and administering river restoration policies, for example for informing CBA.

The CE analysis also identifies significant negative alternative specific constants (ASCs) in both sample groups. The ASC was found to be significantly more negative amongst the River Wey respondents. This suggests that unobserved influences for choosing river improvement options are greater when the anonymity of the river is broken. This is speculated to be the result of 'local stewardship' motivations. As these local stewardship motivations are believed to vary significantly between catchments, they are likely to be a significant issue for benefits function transfer in the context of river barrier mitigation generally (i.e., when calculating compensating surpluses). Environmental attitude is found to be a more consistent predictor of attribute preferences than socioeconomic variables. Consequently, socioeconomic variables are considered unlikely to systematically and successfully explain variation in WTP and correct benefits transfer error in the context of river barrier mitigation. For example, with respect to the differences in IPs for the fish abundance attribute between the national and River Wey sample groups.

Chapter 5 presents a new framework for simultaneously optimizing river barrier mitigation decisions for resident fish and estimating the social economic benefit of investing in this activity (R-FPBRP(V)). This is achieved by incorporating the IPs estimated in Chapter 4 into the R-FPBRP(S) presented in Chapter 3. Embedding the optimization approach within a bio-economic model allows river barrier mitigation policy to be evaluated on the basis of both economic efficiency and cost optimality. This is believed to be crucial if the environmental goals of river barrier mitigation are not to be compromised in light of scarce public economic resources.

The CBA undertaken for the River Wey indicates that implementing a policy of river barrier mitigation in the catchment is economically rational at all budget levels considered. The socially optimal level of investment (i.e. where marginal costs equal marginal benefits) was found to be approximately £30M. This amount is somewhat higher than the investment amounts likely to have been selected using the Pareto-optimal trade-off curves generated from the R-FPBRP(S) model results (as discussed in Chapter 3). The CBA for the River Wey suggests that the continued presence of barriers in many river systems may not be justified on economic efficiency grounds, at least in the UK context.

Given the current drivers for CBA of environmental policy, it is anticipated the framework derived in this thesis will be of direct benefit to both policy makers and practitioners involved in river ecosystem management and barrier mitigation. For example, the WFD specifically requires CBA in catchment management plans in order to direct an efficient allocation of economic resources to the problems of environmental protection. In this regard, the framework presented also benefits from the existence of a statistically robust generic IP for fish species richness improvements (as discussed in Chapter 4), thus rendering it transferable to other catchments of similar scope to the River Wey.

6.2. Further work

6.2.1. Methodological Developments

With regard to future methodological developments, the optimization models presented could be extended in a number of ways. For example, by considering the more general case where river systems are not characterized by a strict dendritic branching structure. This would have been useful in the context of the River Wey, where man-made navigation channels have introduced braids in to the system. The existence of multiple pathways between river subnetworks within the R-FPBRP could then be accommodated using shortest path algorithms to parametrize each subnetwork to subnetwork journey. These algorithms employ graph theoretic approaches, where the river system comprises a graph $G = (V, E)$ characterized by barriers (vertices, V) and connecting river reaches (edges, E). Shortest paths between barriers in the river system could be sequentially evaluated for all the possible inter-barrier subnetwork routes using Dijkstra's algorithm in advance of the optimization process. Alternatively, a more elegant solution would be to employ an all-pairs shortest path algorithm. In fact, given the river system is modified from a dendritic structure, it could be characterized as a sparse graph and shortest paths recovered using Johnson's algorithm (for sparse graphs). Alternatively, the Floyd-Warshall algorithm could be employed to this end. An excellent description of these approaches is provided in Cormen et al. (2009).

Once the distance of each shortest path (π) is determined, the river system could also be represented as a 'shortest-path tree' that is rooted at the river mouth, where $G_\pi = (V_\pi, E_\pi)$. This would provide a structure for estimating the FPBRP model when braiding exists in a river system.

Another interesting line of future research would be to consider different functional forms to describe the relationship between connectivity and fish species responses in the R-FPBRP(S) model, particularly given the non-linear nature of the Poisson regression employed. As noted in Chapter 3, the Poisson regression models the effect of increases in connectivity on the natural log of fish species richness. However, in order to maintain the linearity of the R-FPBRP(S), a linear effect is estimated at the sample mean.

The linearization of logarithmic functions has received some attention in the optimization literature. For example, Camm et al. (2001) present a linear approximation for the maximal expected coverage problem (MECP). The MECP maximizes the expected probability of covering a set of species in nature reserve selection decisions. In the MECP, the probability of species being present in the network is calculated from the compound probability of the interaction of all the reserve selection decision variables and the probability of species presence in that reserve. Hence the problem is non-linear. Camm et al. (2001) overcome this issue by first recasting the problem as a minimization of species absence from the network. They calculate the log of the probability of species absence ($\ln w_i$) from the sum of the natural logs of the interactions of reserve selection decision variables with the respective species absence probabilities. They then approximate the curve of species absence (w_i) versus the log of species absence ($\ln w_i$) using a piece-wise linear curve. Accordingly, the MECP can be recast as a liner model, with the degree of approximation dependent on the number of line segments used to represent the underlying non-linear curve.

This approximation approach to linearize the log curve could be applied to the log linear relationship between species richness and connectivity in the R-FPBRP(S). Research is ongoing in this regard. As an alternative, Polasky et al. (2000) develop a Greedy algorithm to generate feasible solutions to the MECP. However this approach is sub-optimal and was found to provide less favorable results than the linear approximation by Camm et al. (2001).

This issue of choice attribute attendance has also received interest in the CE literature (e.g., Balcombe et al. (2014); Kragt (2013); Campbell et al. (2011)). These studies seek to reveal if specific choice experiment attributes are ignored or given less consideration than others by respondents when making their choices. Campbell et al. (2011) describe an approach where attribute attendance is inferred from a Latent Class Model (LCM). Under this approach a number of classes are specified to represent various respondent processing heuristics with respect to attribute attendance. For example, ignoring the cost attribute, attending to the ecological attributes only or, ideally, attending to all attributes. This is achieved by restricting the marginal utilities for all non-attended attributes to zero in the respective latent class. The presence of attribute non-attendance and associated processing heuristics is then revealed by the distribution of the probabilities of respondents membership of the classes specified. The appropriate range of heuristic processing classes is arrived at by maximizing model fit. Kragt (2013) compare this approach with an alternative, using data stated by respondents on whether they ignored an attribute when completing the CE. Setting marginal utilities to zero for these stated as ignored attributes in an RPL specification indirectly reveals attribute non-attendance if this improves model fit.

Finally, Balcombe et al. (2014) compare two approaches. The first conditions marginal utilities for attributes on respondents stated rank of importance of that attribute in an RPL specification. They then evaluate if there is significant correlation between the two (as would be expected) in order to establish the significance of stated attribute non-attendance. Balcombe et al. (2014) also describe a 'contraction approach', where a coefficient (λ_{jk}) is applied to a functional transformation of the marginal utility estimate for each attribute in the RPL specification. λ_{jk} is essentially derived from the ratio of the stated level of importance of the attribute to the cardinality of the attribute ranking system. This approach reveals how marginal utility contracts as a result of low attribute ranking.

During the course of collecting the river improvement CE data, respondents were asked to state any attributes ignored when making their choices and also to rank attributes in terms of their importance. Accordingly, the approaches described above could be employed to inform further research into attribute non-attendance in the context of preferences for river barrier mitigation. These approaches could also be extended to explore the significance of the framing and scale effects associated with breaking the anonymity of the case study river and the influence of socioeconomic variables on attribute attendance. This could prove insightful with respect to benefits transfer.

The overall CBA approach could also be expanded to consider other ecosystem services. For river systems where the provisioning services of fish are important, this could entail investigation of fish abundance responses to connectivity improvements. This could be accomplished via the addition of a second objective into the objective function of the R-FPBRP(V), as discussed in Chapter 5. Alternatively, the benefits from fish abundance could be included using an ecological production function. this could be specified using fish species richness responses to connectivity improvements and local hydrological characteristics as independent variables. Another interesting line of research would be to assess the impact on flood risks resulting from different river barrier mitigation strategies. Such an approach would likely require detailed hydrological modeling of fluvial flooding risks under different rainfall events. This would then require a secondary objective to be incorporated into the objective function of the R-FPBRP(V) to capture the costs of increased flooding resulting from connectivity improvement. These extensions of the CBA could be facilitated by the existence of markets for edible fish and flood risk insurance.

6.2.2. Applied Developments

In terms of application of the methods presented, doubt exists with respect to the species - connectivity response parameter estimated for the River Wey case study. There are a number of reasons to expect uncertainty with respect to this parameter, for example only 20% of the barriers identified in the River Wey were specifically characterized for passability. Ideally, further applications of the model would be supported with bespoke and comprehensive case study survey data. Applying the R-FPBRP(S) presented in different contexts will provide further insight into the magnitude of the statistical relationship between the C metric and fish species richness. This may inform a more generic approach in the future.

Further research administering similar CEs to different river catchment populations in other regions would add confidence to the validity of the generic IP estimated for increased fish species richness. Also, as Colombo and Hanley (2008) suggest, completing multiple CE for the Var_Wild and Tot_Fish attributes across a range of rivers with varied characteristics may facilitate a pooled approach to the transfer of benefit estimates of river barrier mitigation. This may generate more robust generic IPs for increases in fish abundance.

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Appendices

A. FPBRP Code and Data Files

A.1. OPL Model of FPBRP

```
/*******************************************
* OPL 12.5 Model  * Author: sk * Date: 11.10.13
*******************************************/
/*-----------------------------------------
PARAMETER & SET NOTATION
-------------------------------------------*/
//available budget
float b = ...;
//number of restoration targets
int ntargets = ...;
//range of restoration targets indexed by t
range T = 1..ntargets;
//target objective weights
float w[T] = ...;
//set of all barrier IDs indexed by j
{string} J = ...;
//downstream ID for barrier j, "NA" if none exists
string dsid[J] = ...;
//upstream habitat at barrier j for target t
float ushab[J][T] = ...;
//current passability of barrier j for target t
float prepass[J][T] = ...;
//number of mitigation projects available at barrier j
int nproj[J] = ...;
//mitigation project data structure
tuple project {
  string barid;      //barrier ID of given mitigation project
  float cost; //cost of mitigation project
  float postpass[T]; //array post-mitigation passabilities for each t
}
//set of all mitigation projects
{project} A = ...;
//set of all artificial barriers
{string} Jart = {j | j in J: nproj[j] > 0};
```

```
/*--------------------------------------------
DECISION VARIABLES
--------------------------------------------*/
//project mitigation variables: 1 if project i selected, 0 otherwise
dvar boolean x[A];
//change in cumulative passability for t given implementation of i
dvar float+ y[A][T];
//cumulative passability at barrier j for target t
dvar float+ z[J][T];
/*--------------------------------------------
OBJECTIVE
--------------------------------------------*/
maximize sum(t in T) w[t] * sum(j in J) ushab[j][t] * z[j][t];
/*--------------------------------------------
CONSTRAINTS
--------------------------------------------*/
subject to{
  //budget constraint
  budget:
    sum(i in A) i.cost * x[i] <= b;
  //maximum of 1 mitigation project selected per barrier
  max_1_proj:
    forall(j in Jart)
      sum(i in A: i.barid == j) x[i] <= 1;
  //flow-balance constraints for barriers without a downstream barrier
  flow_balance_root:
    forall(j in J: dsid[j] == "NA", t in T)
      z[j][t] == prepass[j][t] + sum(i in A : i.barid == j) y[i][t];
  //flow-balance constraints for barriers with a downstream barrier
  flow_balance_branch:
    forall(j in J: dsid[j] != "NA", t in T)
      z[j][t] == prepass[j][t] * z[dsid[j]][t] +
        sum(i in A : i.barid == j) y[i][t];
  //1st upper bound on increase in cumulative passability
  flow_bounds1:
    forall(j in Jart, i in A: i.barid == j, t in T)
      y[i][t] <= (i.postpass[t] - prepass[j][t]) * x[i];
  //2nd upper bound on increase in cumulative passability
  flow_bounds2:
    forall(j in Jart: dsid[j] != "NA", i in A: i.barid == j, t in T)
      y[iz[j][t] == prepass[j][t] * z[dsid[j]][t] +
        sum(i in A : i.barid == j) y[i][t];
}
```

A.2. Standard Data File Format

Example from Section 3

```
/*********************************************
* OPL 12.5 Data
* Author: sk
* Creation Date: 3 Jun 2013 at 12:51:03
*********************************************/

b = 50000.0;
ntargets = 1;
w = [1.0];

J = {"1", "2", "3"};
dsid = ["NA", "1", "2"];
ushab = [[5.0], [5.0], [5.0]];
prepass = [[0.5], [0.8], [0.2]];
nproj = [1, 1, 1];

A = {
  <"1", 30000, [1.0]>,
  <"2", 40000, [1.0]>,
  <"3", 20000, [1.0]>
};
```

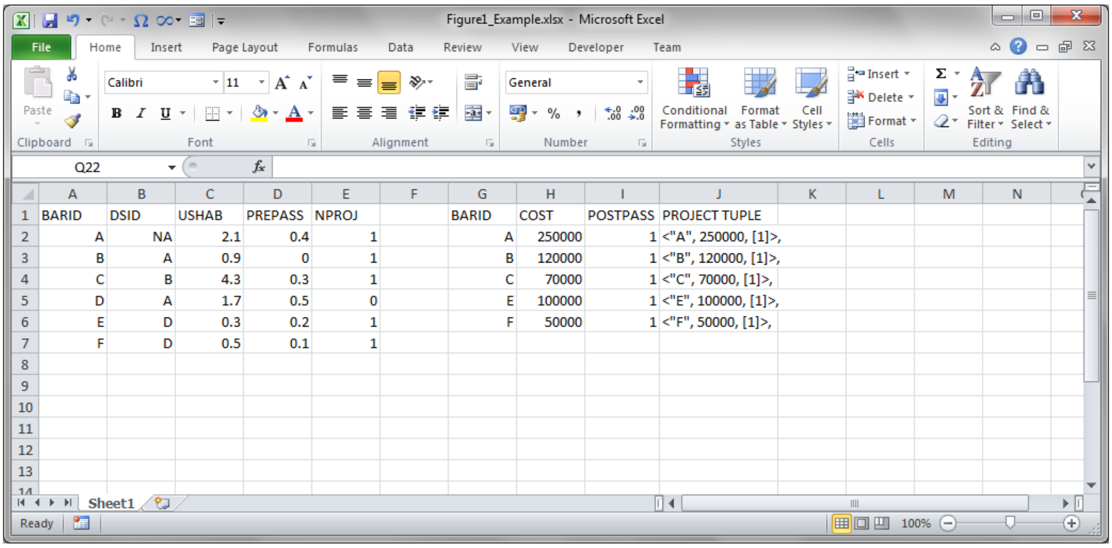
A.3. Extracting Data from an Excel File

Example from Figure 1

```
/*********************************************
* OPL 12.5 Data
* Author: sk
* Creation Date: 3 Jun 2013 at 14:06:55
*********************************************/

b = 200000.0;
ntargets = 1;
w = [1.0];

//establish connection with spreadsheet
SheetConnection data("Figure1_Example.xlsx");
//read in barrier IDs
J from SheetRead(data, "Sheet1!A2:A7");
//read in downstream barrier IDs
dsid from SheetRead(data, "Sheet1!B2:B7");
//read in amount of habitat above each barrier
ushab from SheetRead(data, "Sheet1!C2:C7");
//read in barrier passabilities
prepass from SheetRead(data, "Sheet1!D2:D7");
//read in number of mitigation projects
nproj from SheetRead(data, "Sheet1!E2:E7");

//mitigation projects
A = {
  <"A", 250000, [1]>,
  <"B", 120000, [1]>,
  <"C", 70000, [1]>,
  <"E", 100000, [1]>,
  <"F", 50000, [1]>
};
```

A.4. Excel Spreadsheet

Example from Figure 1



	A	B	C	D	E	F	G	H	I	J
1	BARID	DSID	USHAB	PREPASS	NPROJ		BARID	COST	POSTPASS	PROJECT TUPLE
2	A	NA	2.1	0.4	1		A	250000	1	<"A", 250000, [1]>,
3	B	A	0.9	0	1		B	120000	1	<"B", 120000, [1]>,
4	C	B	4.3	0.3	1		C	70000	1	<"C", 70000, [1]>,
5	D	A	1.7	0.5	0		E	100000	1	<"E", 100000, [1]>,
6	E	D	0.3	0.2	1		F	50000	1	<"F", 50000, [1]>,
7	F	D	0.5	0.1	1					

Figure D1.: Screen shot of Figure1_Example.xlsx.

In OPL, tuples that include arrays cannot be read in directly from Excel. As a work around, column J in Figure D1 is populated with all mitigation project tuples using the CONCATENATE function:

=CONCATENATE("<", CHAR(34), G2, CHAR(34), ", ", H2, ", [", I2, "] >,")

The values in the range J2:J6 can subsequently be copied and pasted into an OPL data file. Note that after copying the cell values in J2:J6 into the curly brackets of set "A" in the OPL data file, the final comma in cell J6 should be deleted (see Appendix C above).

B. Survey Instrument Pretesting

B.1. First Round Summary, November 2012

The first draft of the CE survey instrument was trailed on ten respondents between the ages of 30 and 64 and an equal split of 5 female and 5 male respondents. Respondents generally comprised professional middle calls individuals, largely believed to be representative of the proposed target area for the survey. The findings of the trial for each section of the survey instrument are summarized below.

Introduction

3/10 respondents indicated this section was a bit cold, needed to be more intriguing and engaging about why the work is important. 2/10 suggested swap paragraph 2 & 3.

River Wey System

2 / 10 respondents felt the language was overly technical (e.g., what is a catchment boundary?). 2 / 10 queried Q1(how often use river) as there was no option for daily use (e.g., people who walk their dog daily). 1 / 10 was confused with the use of a household unit in introduction, followed up by these individual questions. 1/ 10 wondered why there was so much focus on angling.

Issues / Improvements / Costs

5/10 respondents suggested the issues could be explained more clearly. 3 / 10 indicated the language was a bit cold / neutral and unengaging. 1 / 10 wondered over what time period the barriers had been established. 3 / 10 indicated the terminology was too scientific (e.g., what is a sluice?, “barriers to movement” etc). 1 / 10 wanted a clearer explanation of public access benefit. 10 / 10 thought the improvements suggested were a good idea and thought it was fair they had to pay for these. However, 3 / 10 felt unfair on locals if visitors also enjoying them. 1 / 10 noted council tax contribution should be graded. 1/ 10 wanted to know if the improvements and tax rises suggested were really being considered. 1 / 10 identified it may be nice to have a river festival for locals to understand work. 10 / 10 accepted the council tax vehicle but 5 / 10 became fixated on the £50 (max value of the cost attribute vector).

Your Views and Choices

6 / 10 respondents indicated the example too messy and hard to work out with all the arrows. These respondents found the choice task intimidating first off and found it hard to differentiate total fish number from diversity in the choice cards. It was also noted that the names for attributes change in arrow and table descriptions. 1 / 10 suggested the annual increase could be interpreted as being compounded. 2 / 10 did not understand the trade-offs offered and indicated a sentence was needed to explain this and what it is about. 3 / 10 did not appreciate the example was an example, rather than a choice task for them to complete. 3 / 10 thought the language was too cold and boring, particularly with respect to the attributes.

Description of Attributes

5 / 10 respondents were confused by the format of the levels presented, having the three levels of improvement in a row seemed similar to the A, B, C option in the example. These respondents generally felt that Option C as the status quo needs to be more clear and that there will always be three options. 2 / 10 the use of 'may offer an improvement' under Option A & B confusing. 4 / 10 thought the attributes too focused on fishing and did not appreciate the social aspect of providing tourism and opportunities for youngsters with respect to recreational angling. Need to stress these benefits. 2 / 10 did not appreciate the diversity attribute had benefits beyond fish. 2 / 10 cleanliness / rubbish expressed as an important attribute not addressed. 3 / 10 identified the idea of a section of river over which the attributes applied was and also wondered why this section was 120m in length. 2 / 10 were confused as to what a good number was for diversity and total fish number and wondered if the River Wey healthy was healthy or not. 2 / 10 noted confusion on meter v mile and No. v number on the attribute levels. 10 / 10 said attributes were meaningful to them. 1 / 10 suggested repetitive to continue to talk of levels after the choice card example .

Options to Improve River

1/10 respondents said the introduction to this section felt like an exam. 1 / 10 indicated they had insufficient information to make their choices. 1 / 10 found it hard to complete the choice task as example confusing (still completed OK though). Some respondents indicted they would have liked more information on the activities that would be possible after improvements, particularly for families. 2 / 10 said there was no need to introduce choice tasks separately. 2 / 10 had concerns on the council tax payment vehicle, this should be clearly indicated to be per year and not compounded. 1 / 10 suggested dragonflies important in biodiversity attribute. 2 / 10 did not appreciate each choice task was independent. 2 / 10 confused by trade-offs as better value options emerge across different choice cards. 2 / 10 rejected DCCV on the basis better value options existed in choice task. 10 / 10 completed choice task correctly indicating it was understandable in retrospect despite 1 / 10 respondent indicating they found it confusing. 9 / 10 considered the CE a worthwhile exercise, appreciating the potential to be involved in their local river management. 10 / 10 indicated they had sufficient information to make choices, although 2 / 10 would have liked more to make a better informed judgment. 10 / 10 indicated costs proposed were reasonable. 3 / 10 were found to have inconsistent preferences, discussion indicated a change in preferences over the choice task as the relative importance of cost, biodiversity and access changed.

About your choices

2 / 10 respondents skipped question 9 as they did not always chose Option C (status quo). 1 / 10 wanted an ‘other?’ option in Question 9 and 10. 2 / 10 not sure if it was OK to tick all boxes on attribute attendance question. 1 / 10 put two attributes as both 2^{nd} most important in attribute ranking. 1 / 10 interpreted the sensitivity of scope question as what they would want if they were actually a local council tax payer.

About You

1 / 10 respondents wanted an example of what a postgraduate qualification was and identified there should be 76 & over category in age question. 10 / 10 were happy and comfortable with these questions.

Environmental Attitudes

1 / 10 wondered how these questions could be answered as a household. 10 / 10 understood format and 3 / 10 said they were fun.

General Comments

The language in the survey instrument was generally considered cold and academic, as such some of the respondents did not find the survey to be engaging. Some respondents appreciated the opportunity (in principle) to be able to provide input into their local river management and suggested this could be stressed more in survey. Some felt the survey was overly orientated towards fisherman. Three respondents felt the survey was too long.

B.2. Second Round, January 2013

The second draft of the CE survey instrument incorporating the feedback from the first round of pretesting was trailed on ten respondents between the ages of 35 and 50, with an equal split of 5 female and 5 male respondents. Respondents generally comprised professional middle calls individuals, largely believed to be representative of the proposed target area for the survey. The findings of the trial are summarized below.

Introduction

2/10 respondents suggested paragraph 2 was bit wordy and could be split in two. 1/10 indicted they felt it was important to stress the survey was impartial (i.e., purely for research).

River Wey System

1 / 10 respondents was unsure of what the term ‘navigations’ meant. 1 / 10 suggested the text should be better linked to the map of the system. 2 / 10 indicated they would like a better quality map. 1 / 10 would like to know where the River Wey finished. 1 / 10 would like opportunity to specify ‘other’ activity for river use question as they are involved in river restoration.

Issues / Improvements / Costs

10 / 10 respondents understood the issues facing the River Wey. 2 / 10 wondered how long the barriers had been established and the reason for their existence. 10 / 10 thought the improvements suggested to the river were a good idea and thought it was fair they should pay for them. However, 3 / 10 felt the notion of the council tax contribution needed to be stressed as hypothetical at this point. 9 / 10 accepted council tax as the payment vehicle, 1/10 rejected it on the basis the improvements should be centrally funded. 2 / 10 had to re-read the ‘one-off increase over 5 years’ to understand the payment vehicle. 1 / 10 worried about the local council wasting the money collected and would prefer it if the Environment Agency were specified as the authority controlling the expenditure on improvements.

Your Views and Choices

1 / 10 respondents rejected the example on the basis of it being too confusing. 2 / 10 suggested the example was easier to understand if the attributes were discussed first. 2 / 10 did not appreciate the example was an example, rather than a choice task for them to complete. 1 / 10 suggested the second paragraph in the section should be bullet pointed.

Description of Attributes

3 / 10 respondents indicated they needed more information on the current level of the attributes to understand how bad the current situation was. Discussion with these respondents suggested that stating they were currently well below natural conditions and, whilst we cannot restore perfect natural conditions, the following levels of improvement could be attained would help establish the context for the CE. 2 / 10 suggested the public access attributes would be better represented in same format as the other attributes (i.e., with a number of symbols that increase). 1 / 10 suggested having a number of walker pictures, which increased from 3 to 6. 1 / 10 expressed confusion over who is responsible for maintaining the river. 1 / 10 found attribute tables confusing and would have preferred them to be split (i.e., have the Option C level then Options A and B and possible improvement levels). 2 / 10 said ecosystem benefit of 'Variety Wildlife' attribute needed to be stressed more. 2 / 10 indicated that cleanliness (e.g. for swimming) / lack of pollution was as an important attribute that was not addressed. 1 / 10 suggested the 120m stretch could be expressed as 2 football pitches or similar. 1 / 10 wondered about the boating dimension. 1 / 10 wanted public access related to the total miles of river and 1 / 10 interpreted the number of miles of accessible river bank as a percentage of the total.

Options to Improve River

1 / 10 respondents refused to complete choice card on the basis that they could not determine how cost varied with the bundle of characteristics provided (was unable to progress the trail any further with this subject). 2 / 10 did not appreciate each choice card was independent. 9 / 10 completed choice cards OK. 1 / 10 wanted a reminder that the status quo was Option C. 1 / 10 indicated they would have appreciated a reminder that this was hypothetical and university research at this point. 1 / 9 rejected DCCV on the basis better value options in choice task. 9 / 10 considered the CE worthwhile exercise, appreciating the potential to be involved in the management of their local river. 9/ 10 indicated they had sufficient information to make choices and that the were also costs reasonable. 1 / 9 had inconsistent preferences.

About your choices

2 / 9 respondents had to re-read the question on whether they always choose the status quo Q3 as they realized they should tick 'I did not always chose Option C' rather than just move on. 3 / 9 said the question on which attributes ignored needed a 'None' option. 3 / 9 did not relate the sensitivity of scope question to their answers. 1 / 9 suggested that the attributes used questions should be first in this section whilst the choice tasks were still fresh in the respondents minds. 1 / 9 wanted an example of what 'the River Wey *generally*' meant in the scope sensitivity

question (e.g., reduced of litter, agricultural pollution etc.). 9/ 9 were happy with the question asking them to rank the attributes in order of importance.

About You

1 / 9 respondents thought having 'primary school' as an educational attainment possibility strange. 7 / 9 were happy and comfortable with these questions, although 2 / 9 were uncomfortable revealing income.

Environmental Attitudes

2 / 9 respondents thought there were too many questions in this section and started employing a heuristic to moderately agree or disagree. 2 / 9 identified some of these questions to be overly vague. 1 / 9 suggested the questions in this section should be separately numbered as clearly different, these questions are answered as an individual not a household. 9 / 9 understood format.

General Comments

The respondents generally felt that it was important to stress that the council tax payments are hypothetical. Generally the survey was received as being interesting and engaging.

C. Pilot Survey

C.1. Introduction

The pilot survey for the Choice Experiment (CE) was administered via email using a word document over February and March 2013. A total of 82 completed surveys were gathered, all of which were useable. Survey responses were initially coded in Excel, converted into comma delimited format and imported into NLOGIT 5 for the econometric analysis. In order to generate a single utility function to inform prior for the final experimental design a MNL specification was employed to model respondents' utility function. The model was estimated using two datasets, one where the first choice card was omitted from the analysis (No CD 1) and one where the seventh was omitted (No CD 7). The rationale for this was that choice card 7 was a repeat of choice card 1 and had been included in order to examine consistency of preferences.

C.2. Results

The MNL model results and Implicit Prices for the CE attributes are summarized in Table C.1.[1] Implicit Prices () for the attributes are also presented in Table C.1,

Table C.1.: MNL Model Results for Pilot Survey

Variable	No CD 1			No CD 7		
	Coef.	P-value	IP (£)	Coef.	P-value	IP (£)
Var_Wild	0.2030***	0.000	15.03	0.1901***	0.000	15.21
$Access$	0.0416***	0.000	3.08	0.0381***	0.000	3.05
Tot_Fish	0.0058**	0.031	0.43	0.0048*	0.074	0.38
$Cost$	-0.0135***	0.000	-	-0.0125***	0.000	-
ASC	-0.6422**	0.016	-	-0.7282***	0.0058	-

*** significant at 1%, ** significant at 5%, * significant at 10%

[1]IPs are calculated using the relationship $IP = \beta_k/\beta_m$, where $\beta_k$is the coefficient for the non-monetary attribute and β_m the coefficient fro the cost attribute. The values reported in Table C.1 reflect the cumulative WTP over the 5 year period the proposed increases in councuil tax would be collected.

A review of Table C.1 indicates similar coefficient values and WTP estimates are derived regardless of whether the first or the seventh choice card is omitted. In accordance with economic theory respondents positively and significantly prefer improvements in wild species diversity (Var_Wild), $Access$ and Total Fish Numbers (Tot_Fish) and negatively and significantly prefer increases in $Cost$. All attributes other than the Tot_Fish are significant at the 1% level. Both datasets reveal a negative and significant Alternative Specific Constant, implying that respondents negatively value the current scenario and wish to move to a level of improvement above the status quo. The only notable difference when estimating the two datasets is that respondents with inconsistent preferences appear to develop an increased preference for increases in the Tot_Fish attribute during the course of the choice experiment. This is revealed by the increased significance of this attribute in the No CD 1 dataset (5% level) compared to the No CD 7 dataset (10% level).

WTP estimates reveal respondents valued an increase in fish species diversity at approximately £15 per species, in access at approximately £3 per mile and Total Fish Number at 40p per fish.

C.3. Conclusions

The results of the pilot survey indicate the imply following specification for respondents deterministic utility function:

$$V = -0.680\,ASC + 0.2\,Var\_Wild + 0.400\,Access + 0.005\,Tot\_Fish - 0.013\,Cost$$

where the ASC of -0.680 is applied where attribute levels remain at the status quo. This specification provides the priors employed in order to revise the experiments design for the final survey instrument.

D. Final Survey Instruments

IMPROVING THE RIVER WEY – WHAT DO YOU THINK?

River Wey near Woking, Surrey

Introduction

Dear Resident of the River Wey Area,

I am a university researcher studying how people value their local rivers. I would be grateful if you would take 20 minutes to complete this survey to help me understand what the River Wey means to you and your household.

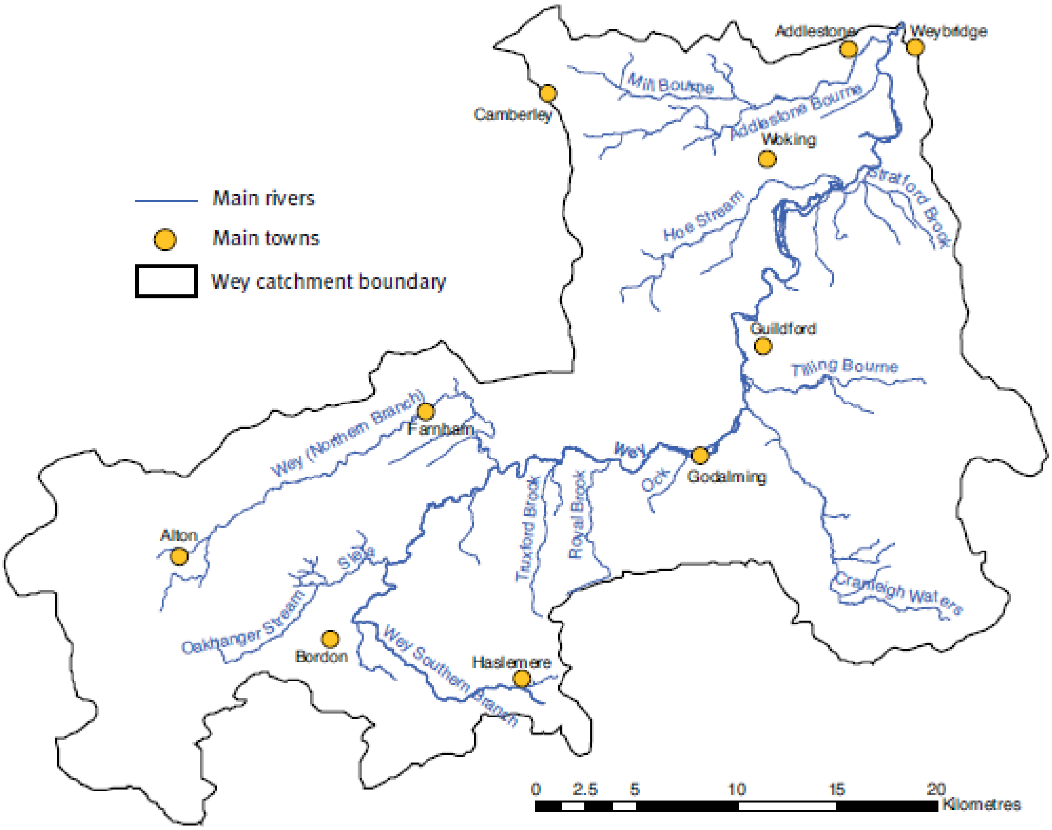
The scenarios presented in this survey are **hypothetical**. However, your responses will provide valuable insight into which characteristics of the River Wey local residents would like to see improved. This will directly inform policy research into how river improvements should be targeted to best benefit local communities and represent their values.

Your participation is voluntary and your responses are strictly confidential. Thank you in advance for your help. If you have any questions, please contact me at the email address below.

Steven King
University of Kent
Email: sk444@kent.ac.uk

The River Wey System

The River Wey comprises two branches, one that starts near Alton in Hampshire and the other near Haslemere in Surrey. The River Wey Navigation (canal), Godalming Navigation (canal) and Basingstoke Canal are also associated with the River Wey system. A map of the system is provided below.



Your use of the River Wey System.

To begin with, I would like to understand how you make use of the River Wey system.

Question 1: In general how often do you visit the River Wey, its tributaries, navigations or canals? Please answer by placing an 'X' in one box only.

☐ About once a day

☐ About once a week

☐ About once a month

☐ Between two and six times a year

☐ Once a year or less

Question 2: Which activities do you participate in when visiting the River Wey system? Please place an ‘X’ in all boxes that apply.

- ☐ Do not participate in any activities
- ☐ Walking the Dog
- ☐ Cycling
- ☐ Boating
- ☐ Walking or Jogging
- ☐ Fishing
- ☐ Nature or Bird Watching
- ☐ Voluntary work (e.g. conservation or maintenance)
- ☐ Other

Issues in the River Wey System

The River Wey system comprises around 190 miles of watercourses providing various places for plants and animals to live, and opportunities for local residents to enjoy the river.

Over the years society has changed the river system by building many river barriers, such as dams and weirs to provide power, road crossings and allow boat travel. However, these also prevent fish and other animals moving freely through the river system and have significantly reduced the numbers of fish and the variety of wildlife in the river system. Also many parts of river bank are privately owned (typically farmland) reducing public access for enjoyment.

The issues affecting fish and other river wildlife can be reduced by removing obsolete river barriers and providing wildlife passage facilities at the ones that are still useful. Public access can be improved by purchasing public access rights to river bank areas.

If money can be raised to fund the above river barrier works and purchasing access rights the following characteristics of the River Wey system can be improved:

- Variety of river wildlife.
- Public access.
- Total number of fish.

Ways to Address the Issues

Given the government has limited resources, one way to provide for the river improvement works listed above would be to raise funds from local residents. Hypothetically funds could be raised by a one-off increase in annual council tax bills that would be paid for five consecutive years only. For example a £20 increase represents five payments of £20 over the five years and £100 in total.

The funds generated would be spent by the Environment Agency specifically on works to improve the River Wey system only. All details of the fund would be made publically available via the internet. Local council tax payers would be invited to an annual river festival where all funded improvements to the river system would be showcased.

BLOCK A

Improving the Characteristics of the River Wey System

As a society we can choose to spend more money on river improvements or not. We can also target how the money is spent. This survey is designed to understand how much local residents would like to be spent on the River Wey system and which characteristics of the system it should be spent on.

In the following sections I will ask you to choose between two different improvement programmes (Options A or B) that can be provided at different costs to your household and a ‘do nothing’ approach (Option C) that will cost your household nothing by completing a series of choice cards.

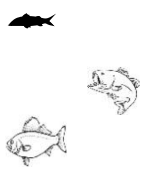
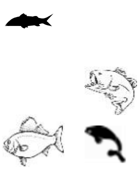
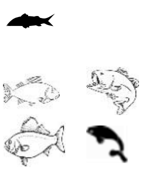
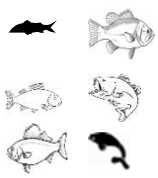
The current variety of river wildlife and the number of fish in the River Wey system is well below that expected under natural conditions. This is represented by Option C. Whilst we cannot return the river to pristine conditions we can improve the connections between different parts of the system by improving fish passage at the barriers (e.g. weirs) that currently exist. Options A and B will offer one of these levels of improvement in variety of river wildlife and the number of fish that could be provided by funding such works.

In addition to improving the conditions for wildlife in the river we can also improve access for public enjoyment. Option C presents the current level of access available, Options A and B will provide an improved level.

The importance and possible level of improvements that will be offered for each characteristic of the system is described below.

<u>Variety of River Wildlife (No. Fish Species).</u>

Increasing the variety of fish in the river system is good for the fish and improves the health of the river environment, providing food for many other animals. This will increase opportunities for viewing iconic species such as the River Otter and Kingfisher and the quality of the River Wey as an educational resource about the environment.

Currently the number of fish species in a typical 120 metre surveyed section of river is 6, represented under Option C by the number and symbols below:	Option A or B may offer you one of the three higher levels of **Variety of River Wildlife (No. Fish species per 120 metre of river)** represented by the numbers and symbols below:		
No Improvement	Low level of improvement	Medium level of improvement	High level of improvement
 6	 8	 10	 12

Publically Accessible River Bank (miles).

Approximately 20 miles of the River Wey and 14 miles of the Basingstoke canal are provided with good quality publically accessible towpaths. However, access to the remaining 156 miles of the river system is very limited. Increasing the miles of accessible river bank paths and public spaces will provide more opportunities for local residents to enjoy river bank environments.

The current level of 34 miles of public access footpath along the banks of river system is represented under Option C by the number and symbols below:	Option A or B may offer you one of the three higher levels of **Publically Accessible River Bank (miles)** represented by the numbers and symbols below:		
No Improvement	Low level of improvement	Medium level of improvement	High level of improvement
34	44	54	64

Total Numbers of Fish.

Increasing the total number of fish makes local fish populations stronger and provides improved recreational angling opportunities. Whilst you may not be interested in angling yourself please bear in mind that in England and Wales 21% of all 12 – 16 year olds have fished in the last two years.

Angling is also recognized as a healthy form of outdoor recreation that promotes environmental awareness, providing physical and mental health benefits to many young and older members of your community. Furthermore, the angling industry is worth £1 billion per year and improved angling opportunities can provide important sources of local income.

Currently the total number of fish in a typical 120 metre surveyed section of river is 90, represented under Option C by the number and symbols below:	Option A or B may offer you one of the three higher levels of **Total No. Fish per 120 metre of river** represented by the numbers and symbols below:		
No Improvement	Low level of improvement	Medium level of improvement	High level of improvement
90	120	150	180

Example Choice Card

In the following section I will ask you to indicate your preferred choice of river improvements by completing a series of choice cards.

You do not need to know about river management to make your choices as there is no right or wrong answers. As people's choices vary I am very interested in your personal choices so I can incorporate them into my research.

An example of how to complete the choice cards is presented below.

The columns for Options A and B are possible improvement programmes to the River Wey system and require you to make increased council tax

The Option C column is the present state of the River Wey System and does not require extra council tax payments.

These rows show characteristics of the River Wey system that would be improved under Option A or B and remain the same under Option C (No improvement).

This row shows the cost to your household of Option A and B.

<u>Example Choice Card</u>	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	64	44	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	**£30**	None

Please tick the **<u>one</u>** option that you most prefer:

	X **Option A**	**Option B**	**Option C**

In one of these boxes you should make your choice by placing an 'X' in the box of your most preferred option based on the changes in characteristics provided by Options A or B. If you feel that the cost of Options A or B is too high there are better things to spend your money tick Option C.

BLOCK A

Options to Improve the River Wey System.

Please complete the following 9 choice cards on behalf of your household.

Whilst the council tax rise presented is hypothetical to inform this research, please carefully consider the amount of money you have available and the other things your household could spend this money so your answers are as realistic as possible. Also bear in mind there are other river systems in the area, e.g. River Thames, for you to use and any improvement offered applies only to the River Wey system.

None of the options presented will increase flood risk, affect boating or increase undesirable / non-native animals or plants in the River Wey system.

Some of the choices may seem strange and one or two characteristics may not even improve under Options A or B. However, your choices help me to understand the tradeoffs you make between characteristics and what they are worth to you.

Please consider each choice card individually and independently of the others.

Choice Card 1	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	64	44	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	**£30**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK A

Choice Card 2	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	8	10	6
Publically Accessible River Bank (miles)	34	64	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£20**	**£20**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK A

Choice Card 3	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	8	12	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£30**	**£10**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK A

<u>Choice Card 4</u>	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	8	10	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£30**	**£10**	None
Please tick the **<u>one</u>** option that you most prefer:			
	☐ **Option A**	☐ **Option B**	☐ **Option C**

Choice Card 5	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	6	12	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	180	90	90
One-off Increase in Council Tax (paid for 5 years only)	**£5**	**£50**	None

Please tick the **one** option that you most prefer:

☐ **Option A** ☐ **Option B** ☐ **Option C**

BLOCK A

Choice Card 6	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	12	6	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	90	180	90
One-off Increase in Council Tax (paid for 5 years only)	**£50**	**£5**	None
Please tick the **one** option that you most prefer:			
	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK A

Choice Card 7	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	64	44	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	**£30**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

Choice card 8 is slightly different and asks if your household would be willing to pay an indicated amount for the indicated improvements in characteristics.

Choice Card 8	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	6
Publically Accessible River Bank (miles)	54	34
Total No. Fish per 120m of river	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	
Are you Willing to Pay the above cost for the environmental improvements provided by Option B?	☐ **Yes** ☐ **No**	

BLOCK A

Choice card 9 asks if your household would be willing the indicated higher amount for maximum levels of improvements that are possible.

Choice Card 9	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	12	6
Publically Accessible River Bank (miles)	64	34
Total No. Fish per 120m of river	180	90
One-off Increase in Council Tax (paid for 5 years only)	**£20**	
Are you Willing to Pay the above cost for the environmental improvements provided by Option B?	☐ **Yes** ☐ **No**	

About Your Choices

I would like to ask you some questions about the choices you have made to help me understand your views on improving the River Wey System.

Question 3: Please indicate any of the characteristics you ignored when making ALL of your choices – please place an 'X' in all boxes that apply.

- ☐ Variety of River Wildlife (No. Fish Species per 120m).
- ☐ Publically Accessible River Bank (miles).
- ☐ Total Number of Fish per 120m of river.
- ☐ One-off Increase in Council Tax (paid for 5 years only).
- ☐ I did not ignore any of the characteristics.

Question 4: Please rank all of the characteristics from 1 to 4 in terms of their importance to you in making your choice – place a 1 in the box for the most important characteristic and a 4 for the least important.

- ☐ Variety of River Wildlife (No. Fish Species per 120m).
- ☐ Publically Accessible River Bank (miles).
- ☐ Total Number of Fish per 120m of river.
- ☐ One-off Increase in Council Tax (paid for 5 years only).

Question 5: Did you always choose Option C (no improvement) in the Choice Cards and if so why? Please place an 'X' in one box only.

- ☐ I did not always Choose Option C.
- ☐ I did not feel improving the River Wey system was worth the increase in council tax.
- ☐ I support improving the River Wey system but cannot afford the increase in council tax.
- ☐ I support improving the River Wey system but object to having to pay extra council tax to fund it.
- ☐ I do not believe that the improvements offered are possible.

Question 6: If you choose Options A or B in any of Choice Cards, please indicate why – place an 'X' in one box only.

- ☐ I wanted to contribute to improved public access and wildlife at the River Wey.
- ☐ I wanted to contribute to improving the conditions of the River Wey system generally.
- ☐ I wanted to contribute to improving rivers generally.

BLOCK A

About You

I would like to ask a few questions about you that will help us to understand how well this survey sample represents residents of the River Wey area. This information will be kept strictly confidential and remain anonymous. Please indicate your answer by placing an 'X' in the relevant box.

Question 7: What is your gender?

- ☐ Female
- ☐ Male

Question 8: How old are you?

- ☐ 16 - 25
- ☐ 26 - 35
- ☐ 36 - 45
- ☐ 46 – 55
- ☐ 56 – 65
- ☐ 66 - 75
- ☐ 76 and over

Question 9: What is your highest level of education?

- ☐ Primary school education
- ☐ Secondary school education or equivalent (e.g. GCSE's / O-Levels / GNVQ / NVQ Level 1 or 2)
- ☐ A-Level (or equivalent, e.g. Higher School Certificate / NVQ level 3 / Advance GNVQ)
- ☐ University degree (or equivalent, e.g. NVQ levels 4 & 5, HNC, HND)
- ☐ Postgraduate degree or equivalent (e.g. MSc.)

Question 10: Do you have children?

- ☐ Yes
- ☐ No

Question 11: Which of the following best represents your household income?

- ☐ less than £20,000
- ☐ £20,000 - £40,000
- ☐ £40,000 - £60,000
- ☐ £60,000 - £80,000
- ☐ £80,000 - £100,000
- ☐ £100,000 - £120,000
- ☐ Over £120,000

Question 12: Are you a member of an environmental or conservation organisation (for example the National Trust)?

- ☐ Yes
- ☐ No

Question 13: Are you a member of any groups that make use of the River Wey system (for example a local angling or boating society)?

- ☐ Yes
- ☐ No

BLOCK A

And Finally - Your Environmental Attitudes

In this final section of the survey, I would like to ask a few questions about the way you view the environment. Please read the following statements and place a tick in the box that corresponds best with your opinion of the statement. Please place an 'X' in one box only for each statement.

Do you agree or disagree that:	Strongly Agree	Moderately Agree	Unsure	Moderately Disagree	Strongly Disagree
14. We are approaching the limit of the number of people the earth can support.	☐	☐	☐	☐	☐
15. Humans have the right to modify the natural environment to suit their needs.	☐	☐	☐	☐	☐
16. When humans interfere with nature it often produces disastrous consequences.	☐	☐	☐	☐	☐
17. Human ingenuity will insure that we do not make the earth unlivable.	☐	☐	☐	☐	☐
18. Humans are severely abusing the environment.	☐	☐	☐	☐	☐
19. The earth has plenty of natural resources if we just learn how to develop them.	☐	☐	☐	☐	☐
20. Plants and animals have as much right as humans to exist.	☐	☐	☐	☐	☐
21. The balance of nature is strong enough to cope with the impacts of modern industrial nations.	☐	☐	☐	☐	☐
22. Despite our special abilities humans are still subject to the laws of nature.	☐	☐	☐	☐	☐
23. The so-called "ecological crisis" facing humankind has been greatly exaggerated.	☐	☐	☐	☐	☐
24. The earth is like a spaceship with very limited room and resources.	☐	☐	☐	☐	☐
25. Humans were meant to rule over the rest of nature.	☐	☐	☐	☐	☐
26. The balance of nature is very delicate and easily upset.	☐	☐	☐	☐	☐
27. Humans will eventually learn enough about how nature works to be able to control it.	☐	☐	☐	☐	☐
28. If things continue on their present course, we will soon experience a major ecological catastrophe.	☐	☐	☐	☐	☐

Thank you very much for doing this Survey.

I hope you enjoyed taking part.

BLOCK A OUT

IMPROVING YOUR LOCAL RIVER – WHAT DO YOU THINK?

Typical River Scene

Introduction

Dear Resident,

I am a university researcher studying how people value their local rivers. I would be grateful if you would take 20 minutes to complete this survey to help me understand what your local river means to you and your household.

The scenarios presented in this survey are **hypothetical** and based on a typical UK case study river. However, your responses will provide valuable insight into which characteristics of local rivers residents would like to see improved. This will directly inform policy research into how river improvements should be targeted to best benefit local communities and represent their values.

Your participation is voluntary and your responses are strictly confidential. Thank you in advance for your help. If you have any questions, please contact me at the email address below.

Steven King
University of Kent
Email: sk444@kent.ac.uk

Your Local River System

To begin with, I would like to understand how you make use your local river.

Question 1: In general how often do you visit your local river, its tributaries, navigations or canals? Please answer by placing an 'X' in one box only.

☐ About once a day

☐ About once a week

☐ About once a month

☐ Between two and six times a year

☐ Once a year or less

Question 2: Which activities do you participate in when visiting your local river? Please place an 'X' in <u>all</u> boxes that apply.

☐ Do not participate in any activities

☐ Walking the Dog

☐ Cycling

☐ Boating

☐ Walking or Jogging

☐ Fishing

☐ Nature or Bird Watching

☐ Voluntary work (e.g. conservation or maintenance)

☐ Other

Issues in UK rivers

Over the years society has changed the rivers by building many river barriers, such as dams and weirs to provide power, road crossings and to allow boat travel. However, these also prevent fish and other animals moving freely through the river system and have significantly reduced the numbers of fish and the variety of wildlife in the river system. Also many parts of river bank are now privately owned (typically farmland) reducing public access for enjoyment.

The issues affecting fish and other river wildlife can be reduced by removing obsolete river barriers and providing wildlife passage facilities at the ones that are still useful. Public access can be improved by purchasing public access rights to river bank areas.

If money can be raised to fund the above river barrier works and purchasing access rights the following characteristics of your local river would be improved:

- Variety of river wildlife.
- Public access.
- Total number of fish.

Ways to Address the Issues

Given the government has limited resources, one way to provide for the river improvement works listed above would be to raise funds from local residents. Hypothetically funds could be raised by a one-off increase in annual council tax bills that would be paid for five consecutive years only. For example a £20 increase represents five payments of £20 over the five years and £100 in total.

The funds generated would be spent by the Environment Agency specifically on works to improve your local river system only. All details of the fund would be made publically available via the internet. Local council tax payers would be invited to an annual river festival where all funded improvements to the river system would be showcased.

Improving the characteristics of your local river.

As a society we can choose to spend more money on river improvements or not. We can also target how the money is spent. This survey is designed to understand how much residents would like to be spent on their local river systems and which characteristics of the system it should be spent on.

In the following sections I will ask you to choose between two different improvement programmes (Options A or B) that can be provided at different costs to your household and a 'do nothing' approach (Option C) that will cost your household nothing by completing a series of choice cards The levels and improvements offered in the choice card are based on a typical UK case study river, that represents across UK rivers generally.

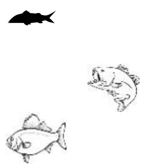
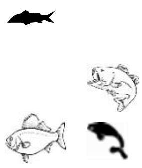
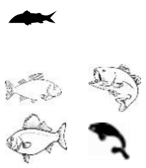
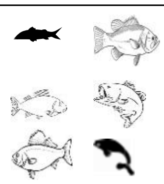
The current variety of river wildlife and the number of fish in UK river systems is well below that expected under natural conditions. This is represented by Option C. Whilst we cannot return the river to pristine conditions we can improve the connections between different parts of the system by improving fish passage at the barriers (e.g. weirs) that currently exist. Options A and B will offer one of these levels of improvement in variety of river wildlife and the number of fish that could be provided by funding such works.

In addition to improving the conditions for wildlife in the river we can also improve access for public enjoyment. Option C presents the current level of access available, Options A and B will provide an improved level.

The importance and possible level of improvements that will be offered for each characteristic of the system is described below.

<u>Variety of River Wildlife (No. Fish Species).</u>

Increasing the variety of fish in the river system is good for the fish and improves the health of the river environment, providing food for many other animals. This will increase opportunities for viewing iconic species such as the River Otter and Kingfisher and the quality of rivers as an educational resource about the environment.

Currently the number of fish species in a typical 120 metre surveyed section of the case study river is 6, represented under Option C by the number and symbols below:	Option A or B may offer you one of the three higher levels of **Variety of River Wildlife (No. Fish species per 120 metre of river)** represented by the numbers and symbols below:		
No Improvement	Low level of improvement	Medium level of improvement	High level of improvement
 6	 8	 10	 12

BLOCK 1 OUT

Publically Accessible River Bank (miles).

Approximately 34 miles of the case study river is provided with good quality publically accessible footpaths. However, access to the remaining 156 miles of the river system is very limited. If this was your local river system increasing the miles of accessible river bank paths would more opportunities for local residents to enjoy river bank environments.

The current level of 34 miles of public access footpath along the banks of the case study river is represented under Option C by the number and symbols below:	Option A or B may offer you one of the three higher levels of **Publically Accessible River Bank (miles)** represented by the numbers and symbols below:		
No Improvement	Low level of improvement	Medium level of improvement	High level of improvement
34	44	54	64

Total Numbers of Fish.

Increasing the total number of fish makes local fish populations stronger and provides improved recreational angling opportunities. Whilst you may not be interested in angling yourself please bear in mind that in England and Wales 21% of all 12 – 16 year olds have fished in the last two years.

Angling is also recognized as a healthy form of outdoor recreation that promotes environmental awareness, providing physical and mental health benefits to many young and older members of your community. Furthermore, the angling industry is worth £1 billion per year and improved angling opportunities can provide important sources of local income.

Currently the total number of fish in a typical 120 metre surveyed section of the case study river is 90, represented under Option C by the number and symbols below:	Option A or B may offer you one of the three higher levels of **Total No. Fish per 120 metre of river** represented by the numbers and symbols below:		
No Improvement	Low level of improvement	Medium level of improvement	High level of improvement
90	120	150	180

BLOCK 1 OUT

Example Choice Card

In the following section I will ask you to indicate your preferred choice of river improvements by completing a series of choice cards.

You do not need to know about river management to make your choices as there is no right or wrong answers. As people's choices vary I am very interested in your personal choices so I can incorporate them into my research.

An example of how to complete the choice cards is presented below.

The columns for Options A and B are possible improvement programmes to your local river system and require you to make increased council tax payments.

The Option C column is the present state of your local river system and does not require extra council tax payments.

Example Choice Card	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	64	44	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	**£30**	None

Please tick the **one** option that you most prefer:

	X **Option A**	☐ **Option B**	☐ **Option C**

These rows show characteristics of your local river system that would be improved under Option A or B and remain the same under Option C (No improvement).

This row shows the cost to your household of Option A and B.

In one of these boxes you should make your choice by placing an 'X' in the box of your most preferred option based on the changes in characteristics provided by Options A or B. If you feel that the cost of Options A or B is too high there are better things to spend your money tick Option C.

Options to Improve your local river system.

Please complete the following 9 choice cards on behalf of your household.

Whilst the council tax rise presented is hypothetical to inform this research, please carefully consider the amount of money you have available and the other things your household could spend this money so your answers are as realistic as possible. Also bear in mind there may be other river systems further away for you to use and any improvement offered applies only to your local river system.

None of the options presented will increase flood risk, affect boating or increase undesirable / non-native animals or plants in the river system.

Some of the choices may seem strange and one or two characteristics may not even improve under Options A or B. However, your choices help me to understand the tradeoffs you make between characteristics and what they are worth to you.

Please consider each choice card individually and independently of the others.

Choice Card 1	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	64	44	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	**£30**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

Choice Card 2	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	8	10	6
Publically Accessible River Bank (miles)	34	64	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£20**	**£20**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK 1 OUT

Choice Card 3	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	8	12	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£30**	**£10**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

Choice Card 4	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	8	10	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£30**	**£10**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK 1 OUT

<u>Choice Card 5</u>	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	6	12	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	180	90	90
One-off Increase in Council Tax (paid for 5 years only)	**£5**	**£50**	None

Please tick the **<u>one</u>** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK 1 OUT

Choice Card 6	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	12	6	6
Publically Accessible River Bank (miles)	44	54	34
Total No. Fish per 120m of river	90	180	90
One-off Increase in Council Tax (paid for 5 years only)	**£50**	**£5**	None
Please tick the **one** option that you most prefer:			
	☐ **Option A**	☐ **Option B**	☐ **Option C**

BLOCK 1 OUT

Choice Card 7	Option A	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	8	6
Publically Accessible River Bank (miles)	64	44	34
Total No. Fish per 120m of river	120	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	**£30**	None

Please tick the **one** option that you most prefer:

	☐ **Option A**	☐ **Option B**	☐ **Option C**

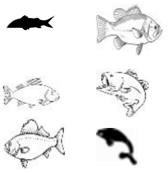
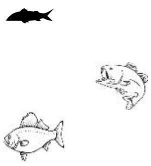
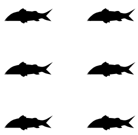
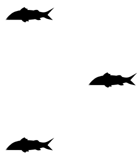
BLOCK 1 OUT

Choice card 8 is slightly different and asks if your household would be willing to pay an indicated amount for the indicated improvements in characteristics.

Choice Card 8	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	10	6
Publically Accessible River Bank (miles)	54	34
Total No. Fish per 120m of river	150	90
One-off Increase in Council Tax (paid for 5 years only)	**£10**	
Are you Willing to Pay the above cost for the environmental improvements provided by Option B?	☐ **Yes** ☐ **No**	

BLOCK 1 OUT

Choice card 9 asks if your household would be willing the indicated higher amount for maximum levels of improvements that are possible.

<u>Choice Card 9</u>	Option B	Option C (No Improvement)
Variety of River Wildlife (No. Fish Species per 120m)	 12	 6
Publically Accessible River Bank (miles)	 64	 34
Total No. Fish per 120m of river	 180	 90
One-off Increase in Council Tax (paid for 5 years only)	**£20**	
Are you Willing to Pay the above cost for the environmental improvements provided by Option B?	☐ **Yes** ☐ **No**	

About Your Choices

I would like to ask you some questions about the choices you have made to help me understand your views on improving your local river system.

Question 3: Please indicate any of the characteristics you ignored when making ALL of your choices – please place an 'X' in all boxes that apply.

- ☐ Variety of River Wildlife (No. Fish Species per 120m).
- ☐ Publically Accessible River Bank (miles).
- ☐ Total Number of Fish per 120m of river.
- ☐ One-off Increase in Council Tax (paid for 5 years only).
- ☐ I did not ignore any of the characteristics.

Question 4: Please rank all of the characteristics from 1 to 4 in terms of their importance to you in making your choice – place a 1 in the box for the most important characteristic and a 4 for the least important.

- ☐ Variety of River Wildlife (No. Fish Species per 120m).
- ☐ Publically Accessible River Bank (miles).
- ☐ Total Number of Fish per 120m of river.
- ☐ One-off Increase in Council Tax (paid for 5 years only).

Question 5: Did you always choose Option C (no improvement) in the Choice Cards and if so why? Please place an 'X' in one box only.

- ☐ I did not always Choose Option C.
- ☐ I did not feel improving the river system was worth the increase in council tax.
- ☐ I support improving the river system but cannot afford the increase in council tax.
- ☐ I support improving the river system but object to having to pay extra council tax to fund it.
- ☐ I do not believe that the improvements offered are possible.

Question 6: If you choose Options A or B in any of Choice Cards, please indicate why – place an 'X' in one box only.

☐ I wanted to contribute to improved public access and wildlife at my local river.

☐ I wanted to contribute to improving the conditions of my local river generally.

☐ I wanted to contribute to improving rivers generally.

BLOCK 1 OUT

About You

I would like to ask a few questions about you that will help us to understand how well this survey sample represents residents of the UK. This information will be kept strictly confidential and remain anonymous. Please indicate your answer by placing an 'X' in the relevant box.

Question 7: What is your gender?

☐ Female

☐ Male

Question 8: How old are you?

☐ 16 - 25

☐ 26 - 35

☐ 36 - 45

☐ 46 – 55

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☐ 66 - 75

☐ 76 and over

Question 9: What is your highest level of education?

☐ Primary school education

☐ Secondary school education or equivalent (e.g. GCSE's / O-Levels / GNVQ / NVQ Level 1 or 2)

☐ A-Level (or equivalent, e.g. Higher School Certificate / NVQ level 3 / Advance GNVQ)

☐ University degree (or equivalent, e.g. NVQ levels 4 & 5, HNC, HND)

☐ Postgraduate degree or equivalent (e.g. MSc.)

Question 10: Do you have children?

- ☐ Yes
- ☐ No

Question 11: Which of the following best represents your household income?

- ☐ less than £20,000
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- ☐ £80,000 - £100,000
- ☐ £100,000 - £120,000
- ☐ Over £120,000

Question 12: Are you a member of an environmental or conservation organisation (for example the National Trust)?

- ☐ Yes
- ☐ No

Question 13: Are you a member of any groups that make use your local river system (for example a local angling or boating society)?

- ☐ Yes
- ☐ No

And Finally - Your Environmental Attitudes

In this final section of the survey, I would like to ask a few questions about the way you view the environment. Please read the following statements and place a tick in the box that corresponds best with your opinion of the statement. Please place an 'X' in one box only for each statement.

Do you agree or disagree that:	Strongly Agree	Moderately Agree	Unsure	Moderately Disagree	Strongly Disagree
14. We are approaching the limit of the number of people the earth can support.	☐	☐	☐	☐	☐
15. Humans have the right to modify the natural environment to suit their needs.	☐	☐	☐	☐	☐
16. When humans interfere with nature it often produces disastrous consequences.	☐	☐	☐	☐	☐
17. Human ingenuity will insure that we do not make the earth unlivable.	☐	☐	☐	☐	☐
18. Humans are severely abusing the environment.	☐	☐	☐	☐	☐
19. The earth has plenty of natural resources if we just learn how to develop them.	☐	☐	☐	☐	☐
20. Plants and animals have as much right as humans to exist.	☐	☐	☐	☐	☐
21. The balance of nature is strong enough to cope with the impacts of modern industrial nations.	☐	☐	☐	☐	☐
22. Despite our special abilities humans are still subject to the laws of nature.	☐	☐	☐	☐	☐
23. The so-called "ecological crisis" facing humankind has been greatly exaggerated.	☐	☐	☐	☐	☐
24. The earth is like a spaceship with very limited room and resources.	☐	☐	☐	☐	☐
25. Humans were meant to rule over the rest of nature.	☐	☐	☐	☐	☐
26. The balance of nature is very delicate and easily upset.	☐	☐	☐	☐	☐
27. Humans will eventually learn enough about how nature works to be able to control it.	☐	☐	☐	☐	☐
28. If things continue on their present course, we will soon experience a major ecological catastrophe.	☐	☐	☐	☐	☐

Thank you very much for doing this Survey.

I hope you enjoyed taking part.