Weir management: challenges, analysis and decision support

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Abstract

If humanity is to make the best of this planet then it is crucial that we develop the capacity to implement the most effective environmental management practices. Essential is a holistic approach to management, as is advocated by integrated catchment management (ICM), which proposes that catchment management issues will be best dealt with when interventions are planned together at the catchment scale and all stakeholder interests are given consideration during decision making. The issue of weir modification is a good example of a problem that would benefit from these principles.

Many stakeholder interests are affected by weir modification, and if effective and fair weir modification decisions are to be made, all must be used to evaluate alternative weir modification options. So that decision makers can make the most of the synergies and avoid the conflicts that can occur between interventions, they need to know how multiple weir modifications interact. To do this decision makers must be able to manage and utilise a large amount of information and use it to help them make effective decisions.

The objective of the research presented in this thesis is to develop an approach to the management of weirs in the Don Catchment that is holistic both a spatial sense and in terms of the assessment of alternative management options. An evaluatory framework for weir modifications is formulated by adapting published typologies of river ecosystem services (ESs). The prediction of how catchment interventions affect sociocultural ESs is recognized as a particularly challenging to the application of this framework because their qualitative and subjective nature makes them hard to predict. Bayesian Networks (BNs) are identified as a potential solution as they use probabilities to describe the relationships between variables. A BN was built to predict how weir modification affected weir danger and weir fun for canoeists by utilising the knowledge of canoeing groups. It is concluded that despite a number of caveats, BNs offer a potentially important method for allowing sociocultural ESs to be predicted in decision making processes.

The consideration of the complex interdependencies multiple weir modifications can have is recognised as another of the challenges facing weir management decision making. A spatially explicit modelling approach is developed that can account for the interactive effect multiple weir modifications have on river connectivity for several river species in the Don Catchment. Expert judgement and hydrological modelling are used to discriminate between different levels of habitat quality for European eel (*Anguilla anguilla*) and Atlantic salmon (*Salmo salar*). Several strategies to increase connectivity in the Don Catchment were explored. It was found that each had its own set of winners and losers, indicating trade-offs between species need to be considered when planning connectivity enhancements. The modelling approach shows the interdependent effects of weir modifications are very important in determining habitat accessibility, particularly the cumulative effect of multiple fish passes.

A decision support system (DSS) dubbed the Weir Tool was constructed through the integration of the canoeing BN and the river connectivity models. As it is generally assumed that if DSS are employed, improved decision making will result, this assumption was tested in a controlled experiment. In contrast to expectations, users of the Weir Tool

learnt less about the environmental issue of weir modification compared to the control group, and did not make more effective decisions.

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1 Introduction

1.1 Weirs: what are they and why are they important?

1.1.1 What weirs are and why they are built

Weirs are low head dams designed to allow the impounded river to flow freely over the crest of the structure (See Figure 1.1). Because they do not affect the volume of river flow they are also known as run-of-the-river dams or overflow dams. It is this that sets them apart from other types of dam, where spillways maintain water levels below the height of the dam crest (Csiki & Rhoads 2010).

Weirs have long been constructed and for many reasons. Archaeologists have found that ancient peoples in the Americas and Eurasia built weirs to trap and harvest fish (Imamura 1996; Erickson 2000; Tveskov & Erlandson 2003), a hunting technique that likely predates the advent of agriculture. Evidently such fish weirs were noteworthy enough in medieval England for one of the conditions in the Magna Carta to stipulate that 'All fish-weirs shall be removed from [...] throughout the whole of England, except on the sea coast' (Holt 1965).

Agriculture is another driver of weir construction that has ancient origins, and is still the reason why many weirs are built today. In regions where water scarcity can limit crop production, weirs are used to divert flows of river water into irrigation networks. In ancient China, India and Mesopotamia, irrigation was of such importance that the construction of weirs was sometimes state sponsored, some of which even gained religious significance (Forbes 1993; Mertha 2008).

The technological innovation that led to the next phase of weir construction is that of the use of water wheels to provide mechanical power for industry like milling. Though the exact date of discovery is obscured by time, the water wheel is believed to have been invented independently in the civilisations of China and the Mediterranean sometime before 0 A.D. (Reynolds 1983). Water wheels are most efficient if water is poured on them from above, so weirs were built to raise the water level of rivers and draw water into side channels (known in northern England as goits). Water wheels were very successful, and through the centuries the technology became increasingly sophisticated; the power they produced utilised by an ever wider range of industries. It was only after the industrial revolution when steam and combustion engines, and the electric motor became available that the use of water wheels finally died out (Reynolds 1983). Water power however has never died out, but instead of generating mechanical power, wheels and turbines are increasingly being employed to generate hydroelectricity, a trend that is likely to continue as the drive for a greater production of renewable energy continues.

As human activities have intensified and diversified through time, so has the need to control and exploit rivers. As a result, lots of new uses for weirs have been found in addition to those discussed above. In the period between antiquity and the present, weirs have been employed to produce a defined cross-section with critical depth flow to measure river flow, prevent the ingress of sea water into rivers, farm fish, make rivers navigable, abstract river substrate, restore rivers, prevent erosion, and to improve landscape aesthetics. Due to this variety of uses, weirs

(a) (b) (c) (d)

Figure 1.1. A selection of weirs, showing some of the variety of forms they can occur in. (a) A roughly built irrigation weir in Morocco only a few centimetres high. (b) Low Matlock Weir on the River Loxley, UK. Several metres high, orientated oblique to the river bank and built as infrastructure for an old water powered iron and steel rolling mill. (c) A stepped weir on the River Porter, UK, approximately one metre high. Its function is unknown to the author, though it might have been built to prevent erosion or be ornamental. (d) Jordans Dam on the River Don, UK, about two metres high with a concave face. Maintains water levels in a navigation. Images taken by the author.

come in many forms. The smallest weirs are only a few centimetres high (e.g. Figure 1.1a), while the biggest can be several metres tall (e.g. Figure 1.1b). Their faces can be stepped (e.g. Figure 1.1c), or smooth (e.g. Figure 1.1d) and have an incline somewhere between a vertical (e.g. Figure 1.1a) or a shallow angle to the river bed (e.g. Figure 1.1d). Relative the river bank they also come in several orientations (see Figure 1.2).

1.1.2 How do weirs affect river ecosystems?

The environmental impact of large dams has received much attention (Baxter 1977; Bednarek 2001; Poff & Hart 2002). Although the impact of weirs is not as extreme as large dams, a substantial body of evidence has now been published which shows that small impoundments can also have a profound effect on riverine ecosystems (Doyle *et al.* 2005; Csiki & Rhoads 2010). Weir impoundment impacts upon river ecosystems by changing the geomorphology, hydrology, physico-chemistry and connectivity of river ecosystems. Here these impacts are reviewed.

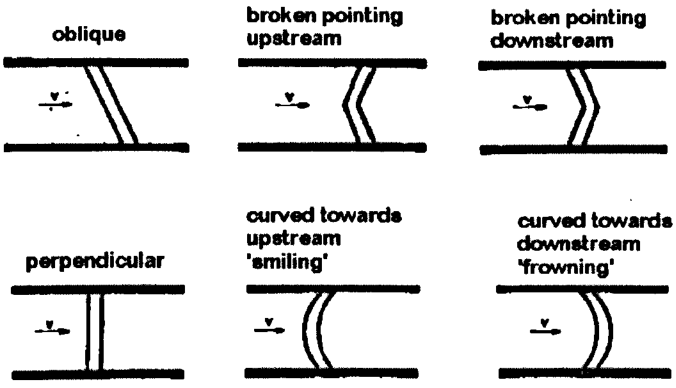


Figure 1.2 . Some of the different orientations weirs can have relative to the river banks.

The geomorphological and hydrological effects of weir impoundment

Weirs raise water levels upstream to the height of the weir crest or higher, submerging land in the river corridor that was formerly dry and increasing the wetted perimeter of the channel. Below the ground, the water table in the riparian zone also rises. As a consequence of the increased river levels and loss of gradient caused be weir impoundment, velocities upstream are reduced (Stanley *et al.* 2002; Pohlon *et al.* 2007; Mueller, Pander, & Geist 2011). This decrease in river velocity can extend several kilometres upstream of a weir, depending on bed gradient (Walter & Merritts 2008).

The deeper, slower river reach upstream of a weir, which Arle (2005) found to be larger than naturally occurring pools on a heavily modified German river, is commonly termed the weir pond, reservoir, basin or impoundment. The residence time of water in weir ponds is usually measured in minutes or hours, while it has been found to be as long as years for large dams (Baxter 1977). The longitudinal profile of the water level upstream of a weir is known as a M1 type backwater curve (see Figure 1.3) (Csiki & Rhoads 2010). The inflection point is a function of the ratio of the height of a weir to river gradient, and migrates downstream and becomes more obtuse as river flow increases (Csiki & Rhoads 2010). The flow of a river before it overflows a weir is subcritical and transitions to supercritical as it passes (Shaw 1994). Downstream of a weir the exact hydraulic conditions depend on the degree of weir submergence (see Figure 1.3) but generally speaking, the high energy turbulent flows can lead to intense scour at the foot of the weir (Tiemann *et al.* 2004; Csiki & Rhoads 2010). Unlike the impact on river conditions upstream, this effect is localised; the energy quickly dissipating before the river returns to more natural flow conditions.

The low energy conditions upstream and the weir structure itself obstructing the transport of large debris can lead to sediment aggradation within the weir pond. Therefore weir ponds often accumulate fine sediments and organic debris in greater quantities than the downstream river (Arle 2005; Walter & Merritts 2008; Im *et al.* 2011; Mueller *et al.* 2011). Sediment aggradation has been found to occur as far as 12km upstream of a weir (Cheng & Granata 2007). Csiki *et al.* (2010) identified catchment, river channel and weir attributes such as relief, soil type, sediment load, flow regime, and weir height and thickness as factors that determine the proportion of sediment that will be captured within the weir pond.

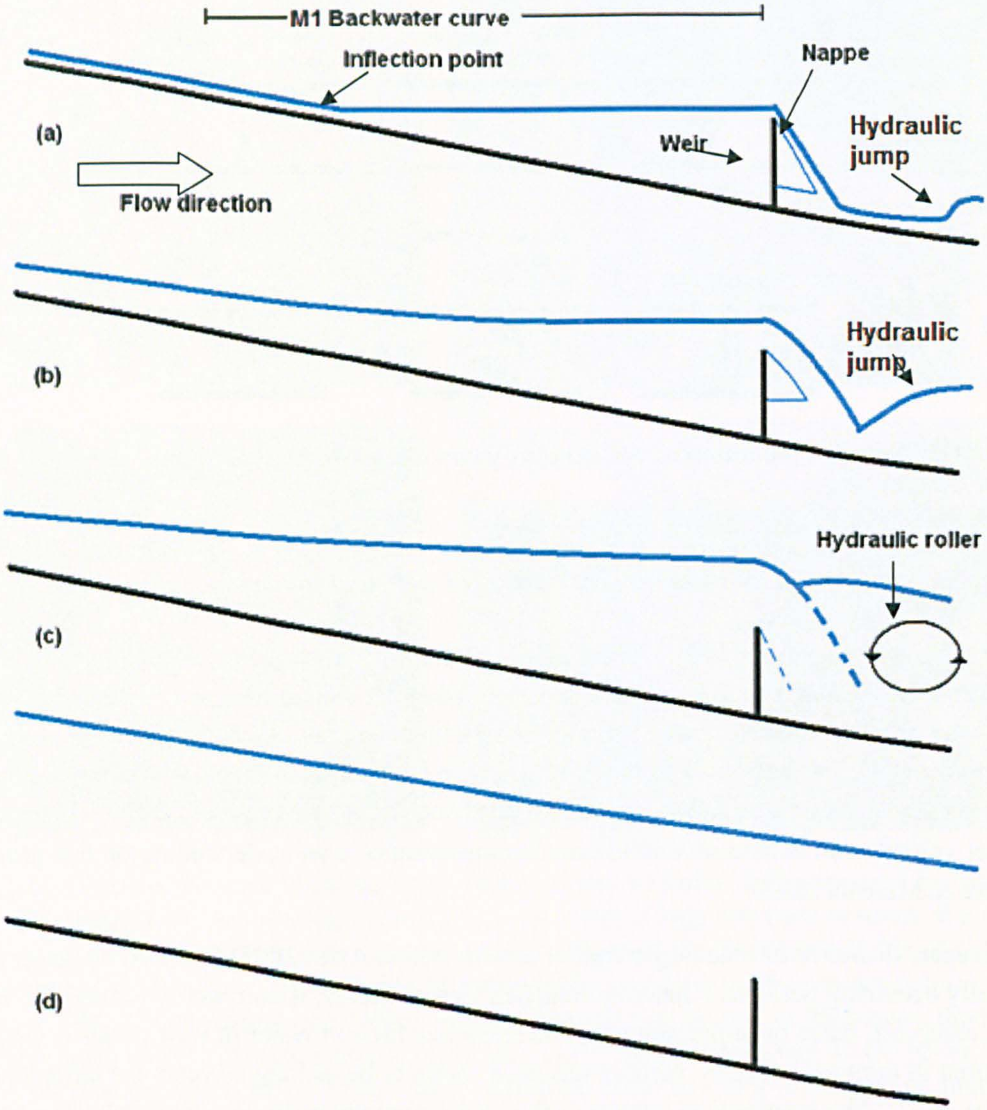


Figure 1.3. The hydrological characteristics of a river flowing over a weir under increasing flow conditions. (a) Low flow conditions with a swept out hydraulic jump. (b) Intermediate to low flow conditions. (c) Intermediate to high flow conditions with a hydraulic roller. (d) A drowned out weir under high flow conditions. The diagram is idealised, and therefore not to scale. *Source*: Adapted from Csiki and Rhoads (2010).

Downstream the high energy conditions, to some degree starved of sediment, can degrade the channel resulting in coarser substrate and the armouring of the river bed (Tiemann *et al.* 2004). Again river substrate, the characteristics of the weir, and the flow regime of the river are important factors that determine the degree of degradation (Csiki & Rhoads 2010).

It has been observed that the propensity for weir ponds to accumulate sediment varies greatly (Csiki & Rhoads 2010). For example little or no sediment was found to have accumulated upstream of a weir in North America (Lindloff 2003 in Csiki *et al.* (2010)), whereas Orr *et al.* (2006) and Walter and Merritts (2008) studied weirs where the weir pond had almost entirely filled up. One of the reasons why this might be the case is that particularly high river flows can sweep away sediments accumulated within a weir pond. Indeed Fjellheim & Raddum (1996) witnessed a river spate 'reset' a weir pond in Norway.

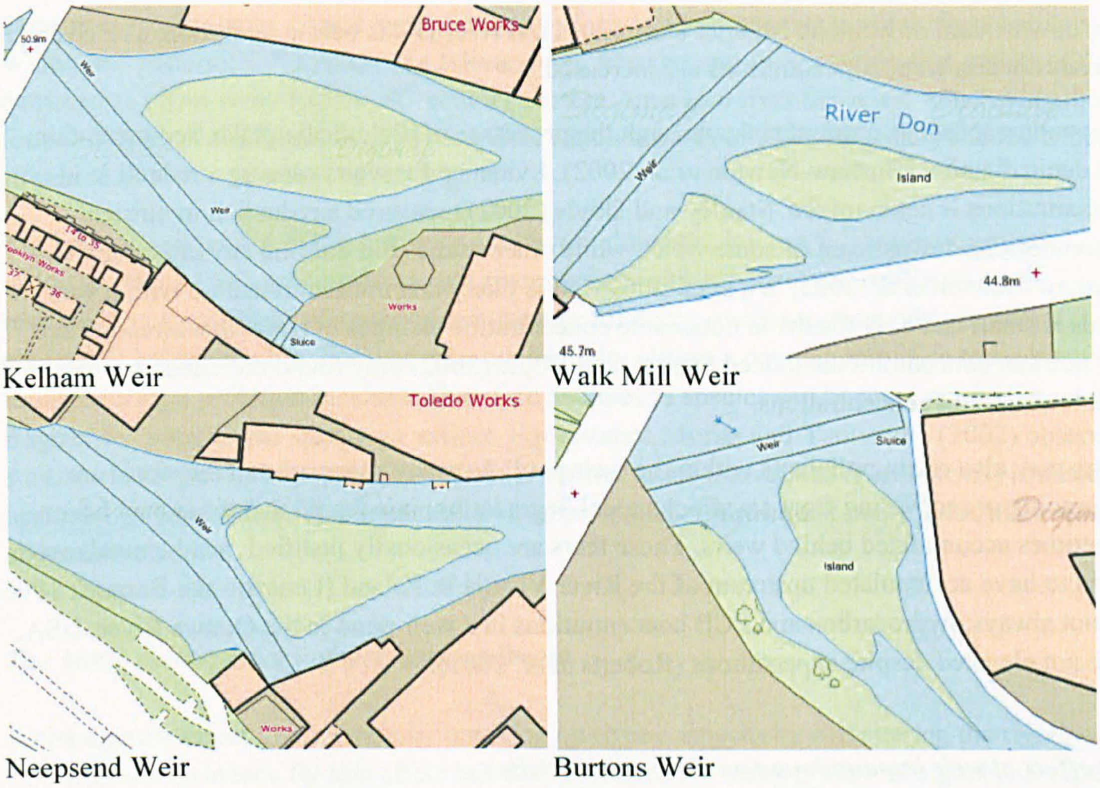


Figure 1.4. Examples of river islands that have formed downstream of weirs on the River Don. *Source*: © Crown Copyright/database right 2011. An Ordnance Survey/EDINA supplied service

However, such resetting does not necessarily always occur. Walter and Merritts (2008) noted that the valleys of impounded streams in eastern USA had developed a stepped topology where each step was produced by the infill of a weir pond. Instead of returning the river to its original state (small anabranching channels with associated wetlands), weir removal caused a single river channel to incise the valley steps.

River islands and bars composed of coarse substrate such as cobbles and gravel often form downstream of weirs (See Figure 1.4). This may be because of the disparity in river depth between the upstream and downstream side of weirs. At the downstream side of the weir, water is too shallow to cover the same width of river bed as upstream.

The physicochemical effects of weir impoundment

Due to the geomorphological and hydrological effects of weir impoundment, the physicochemical characteristics of a river are also altered. Weir ponds tend to cause the accumulation of particulate organic matter (POM), which in turn leads to a higher biochemical oxygen demand (BOD) (Pohlon *et al.* 2007). Combined with the reduction in turbulence, this can sometimes depress dissolved oxygen (DO) concentrations in weir ponds. Santucci *et al.* (2005) measured wide fluctuations in DO concentrations on a daily basis in Illinois, whereas Pohlon *et al.* (2007) found no effect in Germany. The gradient in DO concentrations between the free flowing water column and the interstitial zone was discovered to be greater upstream than downstream of weirs by Mueller *et al.* (2011). If river DO is below saturation, as a river cascades over a weir, concentrations are increased.

Impoundments act as nutrient sinks through the processes of biological uptake, sedimentation, and denitrification (Bushaw-Newton *et al.* 2002). Evidence for weirs causing a reduction in concentrations is again mixed. Stanley and Doyle (2002) measured a reduction in nutrient concentrations downstream of some weirs, while other studies did not find any effect of weirs (Bushaw-Newton *et al.* 2002; Wu *et al.* 2009a). It is likely that nutrient retention within weir ponds is small and only results in noticeable concentration changes in rivers that already have low nutrient concentrations. Indeed Stanley and Doyle (2002) only found the effect in rivers with low nutrient concentrations.

Weirs may also retain pollutants within the weir pool. As many rivers around the world are undergoing or recovering from severe chemical degradation, it is feared that these may have sometimes accumulated behind weirs. These fears are occasionally justified; heavy metals were found to have accumulated upstream of the River Vistula in Poland (Lenczowska-Baranek 1996) but not always; hydrocarbon and PCB concentrations in a weir pond in the Ottawa River, USA, were not elevated despite expectations (Roberts *et al.* 2007).

The effect of weir impoundment on river connectivity

Perhaps the most well known impact of river impoundment by weirs is on river connectivity. Numerous studies have found that weirs often pose insurmountable barriers to fish. For example, weirs have been found to delay or prevent upstream migration of Atlantic salmon (*Salmo salar*) (Gerlier & Roche 1998), European eel (*Anguilla anguilla*) (White & Knights 1997) and common barbel (*Barbus barbus*) (Lucas & Frear 1997). Downstream migration has also been shown to be affected, with fish often reluctant to descend weirs (Aarestrup & Koed 2003; O'Connor *et al.* 2006). Even small weirs can pose significant barriers. Burdick and Hightower (2006) found that the migrations of the anadromous species hickory shad (*Alosa mediocris*), American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*) were obstructed by a 1m tall weir. A weir 30cm high impeded the movement of European river lamprey (*Lampetra fluviatilis*) (Russon, Kemp, & Lucas 2011) and barriers only 20cm high fragment populations of European bullhead (*Cottus gobio*) (Utzinger, Roth, & Peter 1998). While fish have received the most attention, it has also been established weirs hinder dispersal of freshwater prawns (Benstead *et al.* 1999) and plant propagules (Jansson *et al.* 2000). They have not however been found to affect macroinvertebrate drift (Arle 2005).

The negative impact of weirs on migratory species is compounded by increasing the rate of density dependent ecological interactions encountered, including heightened predation, disease, and interspecific and intraspecific competition as individuals accumulate by weirs (Baumgartner 2007). Numerous factors determine the obstructive effect of weirs including weir height, slope, river temperature, flow conditions and depth of water below the weir (de Leaniz 2008).

The consequences of the fragmentation of a river network by weirs for fish can be grave. If an unpassable weir is located at a key migration bottleneck such as the mouth of a river, then this can result in the extirpation of a species from an entire catchment. For example, Atlantic salmon were extirpated from the Meuse Catchment in Europe by weir construction in the 1950s (Kroes *et al.* 2006a). Reyes-Gavilan *et al.* (1996) recorded a reduction in diversity of fish upstream of dams in northern Iberia caused by the inability of diadromous species to reach these habitats. Walter and Merritts (2008) present a telling quote from an anti-weir petition that speaks of the detrimental effect weirs had on 18th century eastern American river fisheries; "destroying the former fishery of shad, salmon, and rock fish, which were before in abundance, and the tributary streams had plenty of trout—all now gone".

The weir driven loss of fish is however not always dramatic, but can in contrast be more insidious. Not all fish are migratory, but river connectivity enhances the resilience and resistance of populations of aquatic organisms by allowing species to respond to temporal changes in habitat quality. For example, connectivity allows a population of fish to seek out refugia during a pollution incident. Therefore declines in species can be more gradual as fragmented populations slowly go extinct. For instance Morita and Yamamoto (2002) observed a trend of extirpation of populations of white-spotted charr (*Salvelinus leucomaenis*) isolated upstream of small dams. The impact of weir impoundment may be felt many years after weirs are constructed.

The biotic consequences of weir impoundment

Weirs directly affect life in rivers by breaking up river connectivity and altering the riverine environment. Evidence for this effect has been collected for many groups of organisms. At the base of the food web the composition of benthic algae communities has been found to be altered by weir impoundment (Hart *et al.* 2002; Wu *et al.* 2009b; Mueller *et al.* 2011). Pohlon *et al.*(2007) found algal abundance and biofilm thickness to be greater within weir ponds compared to unimpounded sites.

A little higher up on the food chain, Shiel *et al.* (1986) noted differences in the zooplankton fauna between the impounded Murray and the unimpounded Darling. Zhou *et al.* (2008) recorded a difference in the composition of the zooplankton community between that in a weir pond and that of the river downstream.

In terms of macroinvertebrates, Arle (2005) found their density to be higher in weir ponds and immediately downstream than at reference sites. Biomass per m^2 however was only significantly higher immediately downstream of the weir, though when the greater river width at weirs was accounted for, biomass per length of river was significantly higher. This contrasts with a study by Tiemann *et al.* (2004) who recorded a lower abundance of macroinvertebrates downstream of a weir, attributed to the negative effect of river scour and the coarseness of the substrate. In a long term study by Fjellheim and Raddum (1996), biomass per m^2 in a weir basin increased rapidly in the years following the construction of a weir, though it varied greatly on a year to year basis.

While macroinvertebrate density and biomass can be higher within weir ponds, species diversity has been found to be significantly less than at reference sites or river stretches downstream of weirs (Stanley *et al.* 2002; Arle 2005; Mueller *et al.* 2011). Weir pond macroinvertebrate communities are typically dominated by filter feeders and gatherers characteristic of lentic habitats such as chironomids, culicids, oligochaetes and caenid mayflies (Bushaw-Newton *et al.* 2002; Hart *et al.* 2002; Tiemann *et al.* 2004; Arle 2005; Santucci *et al.* 2005; Mueller *et al.* 2011). On the other hand, immediately downstream of weirs, Tiemann *et al.* (2004) and Mueller *et al.* (2011) found that the macroinvertebrate community was dominated by shredders, and was characterised by rheophilic species such as rhyacophilid cadisflies, heptogeniid mayfies and leuctrid stoneflies.

Excluding the impact of weirs on connectivity, the change in river habitat brought about by weirs has also been found to influence fish communities. Weir construction in Norway led to a greater abundance of brown trout (*Salmo trutta*) within the weir basin, credited to higher winter survival rates (Fjellheim & Raddum 1996). The weir pond can create a lentic habitat that otherwise may not exist on a river, allowing the colonisation of limnophilic species of fish such as common carp (*Cyprinus carpio*), roach (*Rutilus rutilus*), Chinese false gudgeon (*Abbottina rivularis*) and bleak (*Alburnus alburnus*) into new areas (Doyle *et al.* 2005; Loot *et al.* 2007; Im *et al.* 2011). Mueller *et al.* (2011) found that species richness, biomass and abundance of fish within weir ponds were less than that immediately downstream of a weir. Tiemann *et al.* (2004) also found a preference in a limited number of fish for conditions downstream of weirs. The Neosho madtom (*Noturus placidus*) on the other hand preferred unimpounded river reaches.

In areas with arid climates where flow in rivers may become temporarily reduced or even dry up, the water held behind weirs can serve as refugia in which riverine organisms can wait until the resumption of regular flow conditions. Along the Limpopo River in South Africa, water is held permanently behind weirs, serving as important sanctuaries for animals such as Nile crocodile (*Crocodylus niloticus*) and hippopotami (*Hippopotamus amphibius*) during drought (Jacobsen & Kleynhaus 1993). This creates a dilemma for conservationists, as the same weirs are implicated in the impoverishment and drying up of the Limpopo (Jacobsen & Kleynhaus 1993).

An organism sits in a net of interactions such as predator-prey relationships, competition and mutualism through which it can indirectly affect other species. In this way, weirs have had a seriously negative impact on freshwater mussels (Unionoida). The larval stages of this order of bivalve are spent as obligate external parasites on fish, many of which are migratory species. Therefore, as weirs have prevented fish from entering large proportions of river networks, so have Unionoida been eradicated (Bogan 1993). Many species in the USA, home to a high diversity of Unionoida have gone extinct (Watters 1996).

The impact of weirs also extends out of the river onto the riparian zone. It has been established that the reduction in water level fluctuations in weir ponds is associated with lower riparian vegetation diversity in Sweden (Jansson *et al.* 2000). Regardless of whether the effect always occurs, the high water levels caused by weirs are not necessarily always negative. In Derbyshire, UK, the water levels maintained by Calver Weir on the River Derwent has caused the development of a species rich wetland that is a protected nature reserve.

Conclusions

A diverse set of evidence shows weirs affect all trophic levels of the river ecosystem. Many species of fish have been shown to be particularly detrimentally affected by weir impoundment. While this is likely partly related to the greater quantity of studies focussing on fish (due to their sociocultural and economic importance), it is also probably because in contrast to groups such as emergent aquatic insects, algae and zooplankton that can disperse through the air, many species of fish undergo long migrations during which they are constrained to travel through river networks. As a result, they are more vulnerable to the effects of river barriers. Due to the propensity for fish to travel long distances, the influence of weirs can be felt across whole river catchments, far beyond their geomorphological effects which are relatively localised. Weirs may benefit some limnophilic species of fish, but generally the loss of river connectivity caused by weir impoundment is likely to be detrimental to fish diversity.

The evidence discussed above is not always consistent; different researchers sometimes finding contrasting results. This reflects the heterogeneity and complexity of river ecosystems, and shows different river ecosystems do not respond to weir impoundment in the same way. As a result, general rules on the effects of weir impoundment should be drawn with caution. Weirs are detrimental to many species but not all; there are winners and losers. Impoundment of rivers by weirs does not even always affect the same taxonomic groups in the same way. This means that context is everything when considering how weir construction or modification will affect an ecosystem. An awareness of the range of mechanisms through which weirs interact with river ecosystems is vital if the effects of weir modification are to be predicted and understood.

Generally, the weir pond habitat often consists of homogeneous relatively fine sediments that can have lower habitat diversity or quality than unimpounded river reaches (Tiemann *et al.* 2004; Arle 2005). Weirs can increase the heterogeneity in conditions found in rivers, especially in heavily modified and managed rivers. In natural rivers, log jams, beaver dams and bank collapses can have similar effects to those of weir impoundment (Hart *et al.* 2002). The impact of weirs on shaping river ecosystems is large. Mueller *et al.* (2011) found that the difference between river ecosystems immediately upstream and downstream of a weir was greater than the differences between those of rivers in different catchment with varying geology.

1.1.3 How numerous and widespread are weirs?

Without a doubt weirs are very widespread structures, occurring on all continents apart from Antarctica. The reason for this is the important uses weirs currently have or historically have had. Walter and Merritts (2008) present historical literature documenting the proliferation of water wheel technology after its invention throughout Eurasia, for example showing that in 1700 AD, France had 80,000 water wheels. The colonial era then led to the export of water wheel technology to other parts of the world. By 1840 872 counties of eastern United States had >65,000 weirs (Walter & Merritts 2008). Age, obsolescence, abundance, and perhaps a perception that weirs were of relatively minor importance has resulted in the compilation of few inventories on the numbers of weirs that exist in various countries (Poff & Hart 2002). Where national or regional figures exist the numbers recorded are great (Table 1.1), suggesting the global number of weirs must be vast.

1.2 Weirs and decision making

1.2.1 Weir modification

The obsolescence of water wheel technology means that in many countries such as the UK, weirs are built in less numbers and a large proportion of those that do exist are no longer needed.

Table 1.1. Numbers of weirs recorded in countries, regions or rivers around the world

Number	Country, region or river	Reference
2,000,000[1]	Continental USA	National Research Council (US). Water Science and Technology Board.
3700[2]	Wisconsin, USA	Stanley and Doyle (2002)
16,725	England and Wales	Environment Agency (UK) (2010a)
>1000	Denmark	Aarestrup and Koed (2003)
56	River Ilm (137km), Germany	Arle (2005)
Thousands	Hungary	Kroes *et al.* (2006b)
18,000	South Korea	Woo *et al.* (2005)
4000	New South Wales, Australia	Gehrke and Harris (2001)

[1]Number of low capacity (mean 6170m^3) dams estimated by US Army Corp of Engineers
[2]Total of all dams recorded though majority stated to be weirs

But this does not mean that weirs are no longer a concern of catchment managers. Ecosystems in numerous rivers in the UK are recovering after decades of heavy pollution so there is a growing interest within communities in their future and the benefits healthier rivers can bring (Tunstall *et al.* 2000; Palmer *et al.* 2005). Weirs can have an important role in shaping future rivers. As there are numerous groups (henceforth referred to as stakeholders) with aspirations and visions for the future of river ecosystems, a heterogeneity in the benefits rivers can provide to society there are therefore a number of modifications to weirs that can be potentially implemented.

To try to restore river connectivity, fish passes can be installed on weirs. A fish pass is 'any form of conduit, channel, lift, other device or structure which facilitates the free passage of migrating fish over, through or around any dam or other obstruction, whether natural or man-made, in either an upstream or a downstream direction' (Armstrong *et al.* 2010). There are a wide variety of species of fish with their own swimming style and ability and behaviour when confronting a barrier (Kemp & O'Hanley 2010). This combined with the diversity of weirs and rivers means that there are many different types of fish pass (Armstrong *et al.* 2010) (For two examples see Figure 1.5 a, b). If funds are limited or the weir is small, then modification can be less precise. A notch may be cut in the face of the weir, enabling fish to pass through, or debris may be piled on the front of the weir to produce a makeshift rock ramp (See Figure 1.5 c).

Weirs may also be modified to make them more impassable, desirable when they are preventing the spread of invasive species. For example, in the Don Catchment, UK, the possibility of installing a steel rim along the crest of weirs is being investigated as a way of preventing the spread of the alien signal crayfish (*Pacifastacus lenticulatus*) (Crayfish Action Sheffield 2011).

Modification to weirs is also of interest to some recreational groups, such as canoeists. Weirs can be dangerous for canoeists to descend because of the risk of physical damage and the drowning risk posed by hydraulic rollers that can form at the foot of a weir (Sheffield City Canoe Club pers. comm.). Therefore a structure known as a canoe pass can be installed on a weir, safely conveying the canoeist beyond the dangerous hydraulic conditions present at the foot of a weir.

With the objectives of improving river connectivity and reducing flooding, weirs are sometimes lowered, or to additionally and simultaneously increase the quantity and quality of river habitat, they are increasingly being removed (See Figure 1.5 d, e).

Another modification that is becoming more frequent is that of the installation of microhydro schemes to weirs. The threat of global warming is putting pressure on nations around the world to produce renewable energy, and so the head of water weirs create is being exploited to produce hydroelectricity. A turbine can be installed directly onto a weir (See Figure 1.5 f), or electricity can be generated from a water wheel placed within the water diversion channel (goit) of an old mill. As electricity produced is a function of the head of water at a microhydro scheme, another weir modification option of interest to proponents of hydroelectricity is the raising of weir heights.

Lastly, not all stakeholder groups would like weirs to be modified. Lots of people attach significant heritage value to many of the weirs in the Don Catchment, due to their considerable age, and the noteworthy role they have had in the industrial history of the region. Some would have reservations about major modifications to the most historically valuable weirs.

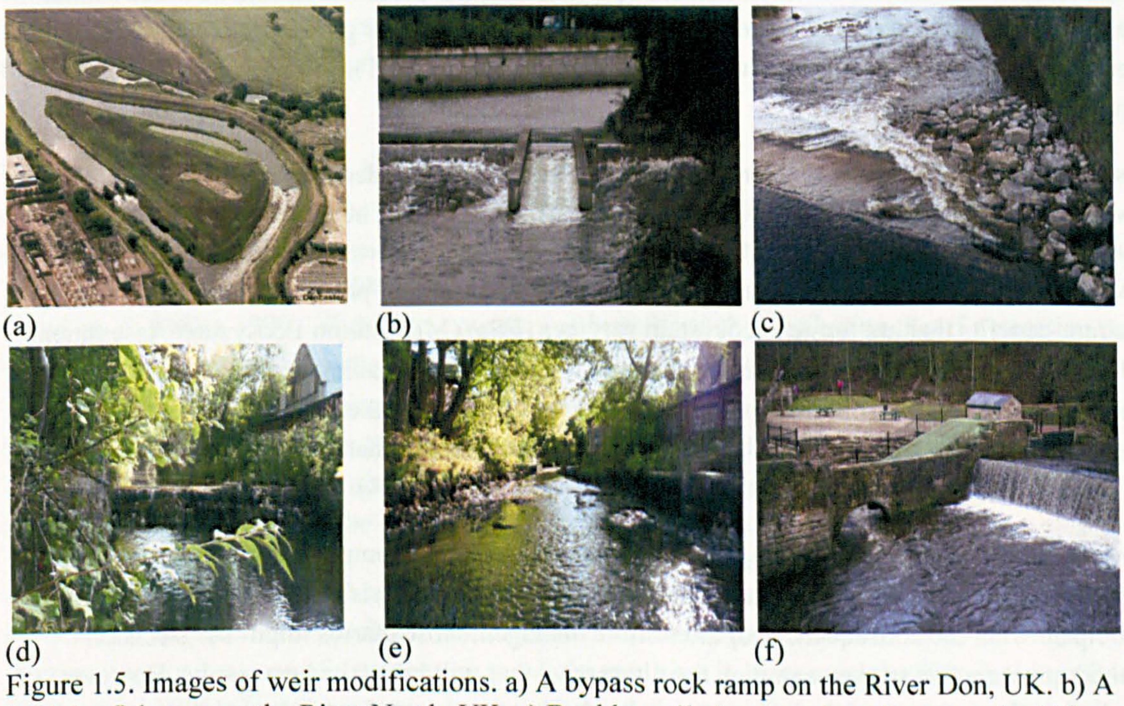


Figure 1.5. Images of weir modifications. a) A bypass rock ramp on the River Don, UK. b) A Larinier fish pass on the River Neath, UK. c) Boulders piled on a weir to form a makeshift rock ramp in the River Don. d) Before a weir was removed on the River Sheaf, UK. e) After the weir (d) was removed. f) A microhydro scheme installed on the River Goyt, UK.

Sources: (a) and (b) in supplementary information with Armstrong *et al*. (2004), c) image taken by Dr Cheryl Gibson and was previously on the web-based image hosting service Flickr, (d) and (e) Yorkshire Fisheries Newsletter Nov 2011 published by the EA, f) picture by the author.

1.2.2 Why is planning weir modification difficult?

The variety of weir modifications discussed in the previous section indicates the diversity of interests people have in river ecosystems and that there is a desire to actively shape the river ecosystem so that aspirations can be realised. But for several reasons, it may not always be possible to meet all of these. Firstly, weir modifications are expensive. For example, a fish pass may cost up to or in rare occasions even exceed £500,000 (Armstrong *et al.* 2010). Therefore there are too many weirs in existence for it to be financially viable to modify them all. Secondly, there is not an exact correspondence between what modifications are required to achieve the aspirations of the different stakeholder groups. Those advocating the development of microhydro schemes may want to preserve and heighten weirs, whereas others wanting to renaturalise rivers may wish to remove them. It is not possible to do both. Therefore catchment management decisions must be made; which weirs should be modified, and what balance should be struck between potentially competing interests?

This catchment management decision making is notoriously difficult (Jamieson 1986; Jakeman & Letcher 2003). Most management problems have numerous stakeholder groups who have potentially competing economic, environmental or sociocultural interests in the outcome of management. Decision making involves finding a trade off between the interests of these stakeholders who may have very different opinions on what decisions should be made (Soncini Sessa, Castelletti, & Weber 2007). If the interests of a stakeholder group are excluded from the decision making process, it can lead to them feeling alienated and hostile towards the resultant final decision (Harding 1998).

As well as human interests that have stakeholder representation, decision makers need also to be aware of the consequences of decisions that will affect aspects of human welfare not lobbied for by interest groups. This can arise for example through a lack of awareness of some aspects of a decision that will affect human welfare. The natural environment provides multiple human welfare benefits that are termed ecosystem services (ESs) (Millennium Ecosystem Assessment 2003). Some of these have not been considered in the decision making process because the existence of an ES may not be appreciated, there may not be a stakeholder group to champion the provision of an ES, the supply of an ES may not have been financially valued (Defra 2007a), or an ES is assumed to be non-limiting (Harding 1998; Chee 2004).

Even if the difficulties of including and negotiating acceptable compromises between stakeholder interests are ignored, the other major challenge of decision making is the need to anticipate what the consequences of alternative management scenarios might be. Decision makers must do this so they can pick the alternative that will bring the best results. However, predicting the outcome of decisions is very hard. The dynamics of natural systems are complex enough, but are made even more so by human interaction (Jakeman & Letcher 2003). The coupling of human and natural systems results in yet more propensity for nonlinear dynamics with thresholds, feedback loops, time lags, resilience, and heterogeneity, and chaos (Liu *et al.* 2007). This overwhelming complexity challenges the capacity of the human mind to make decisions, being only able to receive, process and remember a limited amount of data (Miller 1956). Therefore catchment management problems such as weir modification decision making push the ability of humans to make decisions to the limits.

1.2.3 What is the solution?

Given that effective decision making in catchment management is necessary for the long term existence of humankind, it is unsurprising that the implementation of catchment management is a major research area. This has driven the development of the catchment management paradigm of Integrated Catchment Management (ICM); widely extolled (under various names) by both theorists and practitioners as an approach that promises to improve the making of difficult catchment management decisions like the planning of weir modifications (Jamieson 1986; Mostert 1999; Pascual 2007). Its potential has been recognised at a high level in some political institutions, and has led to its promotion in the legislation of the Water Framework Directive (WFD) (EC 2000) and its implementation in Australia (Mitchell & Hollick 1993).

ICM differs from how catchment management has conventionally been done in a number of regards. Traditionally, the planning of management interventions has been disjointed because different institutions have been responsible for different stakeholder interests (Jamieson 1986). For example, one governmental department might deal with flood control independently of another dealing with fisheries. The product of this is fragmented decision making, which at best is inefficient because opportunities to plan interventions together are lost. For example, both departments might advance their causes further if they collaborated while developing a strategy of weir removal that allowed them to pool their resources. At worst, decision makers operating independently can undo each other's work such as the flood control department removing a weir that was stopping the spread of an invasive species that the fisheries department was trying to control.

To achieve this collaboration, ICM necessitates that those officially responsible for catchment management are brought to the same decision making table so that together they can plan and coordinate activities (Jamieson 1986). And in addition to officially designated decision makers, ICM also requires all stakeholders to be included in the decision making process (Argent, Grayson, & Ewing 1999). There are a number of benefits to this, including that if a decision can be agreed upon with their participation then they are more likely to 'buy in', there is an increased chance of the decision being politically acceptable in the long term, and stakeholders have opportunity to bring valuable additional knowledge into the decision making process (Harding 1998). Of course there is also the normative view that regardless of these benefits, stakeholders morally should be included.

As well as being holistic with regard to the consideration of stakeholder interests, ICM is also holistic in a spatial sense. Catchment management has in the past tended to focus on single interventions or portions of a catchment at a time, resulting in piecemeal decision making (Born & Sonzogni 1995). This is recognised as being unsatisfactory as many processes such as the drainage of water or the migration of fish occur at the catchment scale. This is why a principle of ICM is for catchment managers to plan and make decisions at the catchment scale. As was mentioned earlier, spatially separated interventions like multiple weir modifications can potentially interact in synergistic or conflicting ways, so only by planning at the catchment scale can many issues be effectively addressed (Holzkämper, *et al.* 2012).

If the tenets of ICM are systematically and consistently applied, proponents of this approach expect that it will deliver a rational and efficient allocation of resources, minimise conflict, and promote innovation (Jamieson 1986; Pascual 2007). Unfortunately, as will be discussed in the next section, actually implementing ICM is far from easy.

1.2.4 How can the integrated catchment management of weirs be implemented?

Currently ICM is more of an ambition than an actually practiced approach to catchment management. There are a number of reasons for this. The institutions and leaders who have the power to bring ICM into usage may be reluctant to do so (Lerner *et al.* 2011). Institutions often have entrenched bureaucracies that are resistant to the operational changes ICM requires, preferring instead to stay within their comfort zones (Rogers, Roux, & Biggs 2000). Additionally political squabbling can hinder the uptake of ICM (Mitchell & Hollick 1993). Change for the greater good is consistently sabotaged by politicians when it is politically expedient to do so. Ultimately it is up to the enthusiast of ICM to champion its cause, to persuade those in power of the merits of the approach so that there is enough pressure on political systems to bring ICM into policy. Political scientists might also be able to catalyse this process by advising on ways of structuring political mechanisms so that the conflict between self interest and the greater good is minimised.

But even when there is a political willingness to embrace the philosophies of ICM, actually implementing it is very challenging. Formulating the framework of evaluatory criteria with which different management options can be assessed is a far from trivial task (Belton & Stewart 2002). All stakeholder interests must be considered in the decision making process as criteria with which alternative management scenarios can be judged (Soncini Sessa *et al.* 2007). Yet identifying these criteria is far from simple. What might be assumed by the unfamiliar to be a single stakeholder group interested in a discrete criterion may actually be divided into multiple potentially competing groups, each requiring their own criterion. For example, anglers can often be divided into two groups, each specialising in catching a different type of fish; fly anglers targeting salmonids and coarse anglers targeting limnophilic species. These can then be broken down further, such as into spatially segregated groups who could well be in competition for the resources to promote their local areas for angling, or to a greater degree by the species of fish they prefer to catch. Splitting can go on until you are left with individuals with their own specific set of interests. The problem for catchment managers is to as far as possible be inclusive of all stakeholder groups, but practicalities dictate that not every conceivable stakeholder group can always be involved in the decision making process. There is no correct solution to this problem, rather stakeholder groups must be lumped or split, and as many of the disparate interests as possible must be brought into the decision making process, in a fair and equitable manner without undermining the capacity to conduct ICM.

In addition to the criteria that have stakeholder groups representing them, the implementation of ICM requires that all other aspects of a decision that will affect human welfare be considered as evaluatory criteria during decision making. The oversight of such criteria has been one of the main reasons the capacity of the earth to support humanity has been eroded through time (Vitousek *et al.* 1997). Often neglected are some of the benefits ecosystems freely provide, which is one of the reasons the ES concept was developed. So that no ESs are overlooked during environmental management decision making, comprehensive typologies of all the ES that can potentially be supplied by ecosystems have been developed (e.g. de Groot, Wilson, &

Boumans 2002). Decision makers can then go through the typology of ESs, identifying those that will be affected by their interventions and then use these as the criteria with which alternate environmental management scenarios can be assessed (Fisher, Turner, & Morling 2009). Because by definition they encompass all the benefits people derive from ecosystems, they automatically cover all the criteria that should be considered in decision making. Therefore ES should make a good evaluatory framework of criteria with which to conduct the ICM of weirs.

Once the evaluatory criteria have been identified, the effect alternative management scenarios will have on the criteria must be forecast if the decision makers are to find the best management options. This poses one of the biggest barriers to the implementation of ICM. As early as the 1950s and 60s, the prediction of the consequences of catchment management interventions was being attempted using computer run models (Reuss 2003; Singh & Frevert 2006). But even today, there are many questions as to how such modelling should be done (Lerner *et al.* 2011; Holzkämper, *et al.* 2012). This is partly due to the many challenges associated with modelling coupled human environmental systems, which as was stated earlier, can result in very complicated system behaviour (Liu *et al.* 2007). Another modelling challenge is the prediction of the criteria that reflect sociocultural interests (Schaich, Bieling, & Plieninger 2010). Such criteria are difficult to model as they and the variables that predict them are often qualitative and subjective concepts. For example, weirs pose a threat and provide fun to canoeists. As perceptions of weir danger and weir fun are held within the minds of canoeists, they cannot be modelled using mechanistic processes. However sociocultural interests are important criteria that need to be considered during the implementation of ICM, and so finding ways to predict how decision alternatives affect them is of great importance. Also posing a major difficulty to the implementation of ICM is the prediction of the impact of management scenarios that are composed of multiple interventions, as these can interact to produce an interdependent effect. For example, in the case of managing weirs, multiple weirs can influence the same catchment process such as fish migration. Hence multiple management interventions can interact in a way that reinforces or dampens the effect of each. The development of approaches that can deal with such interdependence is accordingly a research priority of ICM (Jakeman & Letcher 2003).

Questions regarding how ICM should be implemented do not end with how models can predict the evaluatory criteria. An area of debate in ICM regards how the information generated by the models should be used to select the best management scenario as there are a number of approaches that can be taken. One prescriptive way is to weight the criteria with estimates of their importance and then sum the result so that the management scenario with the highest score is the one recommended for implementation (Zeleny 1982). But because different economic, social and environmental criteria are measured using their own units, and as their perceived importance is subjective, intangible, multifaceted and contentious, it is often not practical to use such weightings (Zeleny 1982).

Another fairly rigid way to select the best management options is to find the optimal tradeoffs between the criteria, so that a set of scenarios are identified where one criterion cannot be improved without resulting in a decline in another criterion. Such a scenario is said to lie on the Pareto frontier (Soncini Sessa *et al.* 2007) (see Figure 1.6). The precalculated set of scenarios can be presented to those participating in the decision making process so that they have the freedom to negotiate which of the optimal scenarios should be chosen. It is assumed that the management scenarios found to be suboptimal are inferior to those on the Pareto frontier. But this rigid process does not fit with the messy reality of decision making, which as Zeleny (1982) puts as 'a complex search for information, full of detours, enriched by feedback from casting about in all directions, gathering and discarding information, fuelled by fluctuating uncertainty, indistinct and conflicting concepts – some sharp, some hazy'. This means that the work that an optimisation algorithm does to find the Pareto frontier is the very work that those in the decision making process need to do to get to grips with the decision problem, to identify the knowledge they hold that is significant to informing the process, and to build trust in the results of the models. Without doing this, the management alternatives on the Pareto frontier cannot be assumed to be optimal. For this reason it is suggested that optimisation should not replace the exploration of different management alternatives by decision makers, and the development of their own management scenarios. Yet this is not to say that optimisation does not have a place in ICM. When the decision makers have come up with a scenario they feel confident will perform well, it is useful compare the performance to those scenarios on the Pareto frontier. If it is suboptimal, the question that should then be asked is whether there is additional information that the decision makers hold that has not been fed into the models, meaning the Pareto frontier is not valid and their scenario is not suboptimal, or does the Pareto frontier tell them that there is a scenario available with a performance better than their own?

This raises the next question; how can decision makers explore and design catchment management scenarios? To do this tools are needed to integrate the models underlying the evaluator criteria so that alternative management scenarios can be conveniently compared (Holzkämper, *et al.* 2012). Such integrated models that have been incorporated into a single computer based package with a user-friendly interface to produce a decision making tool are

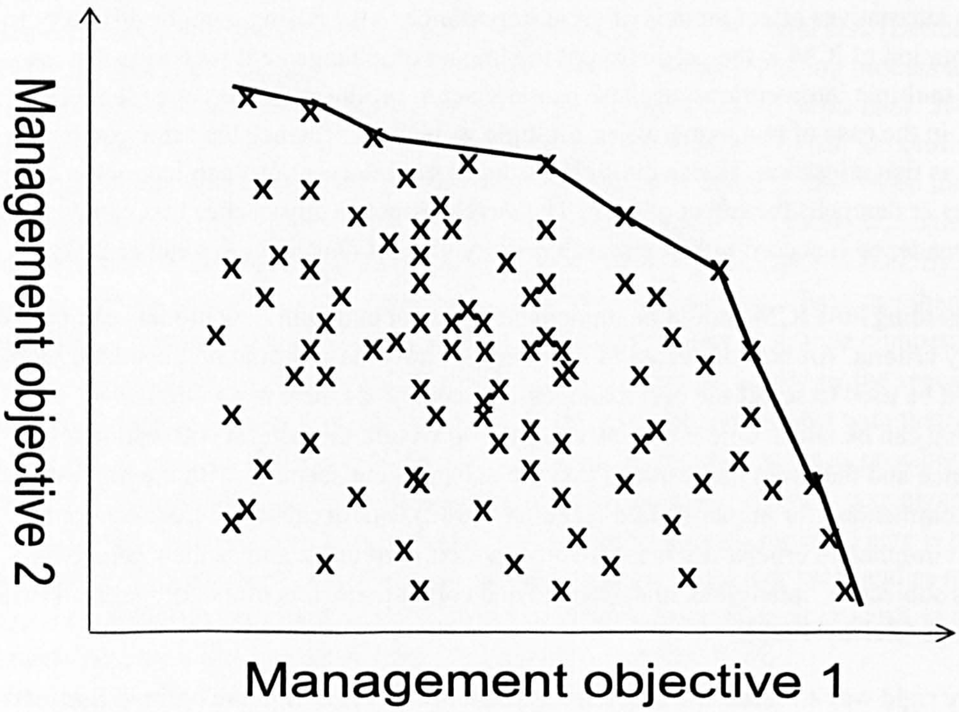


Figure 1.6. A hypothetical example of decisions (the crosses) plotted against their performance with regard to two management objectives. The area in which the decisions lie is termed the decision space. The line is the Pareto frontier and connects those decisions for which no improvement of one management objective can be made without trading off another. Decision making usually involves more than two management objectives, and in such circumstances the decision space has as many dimensions as objectives.

known as Decision Support Systems (DSSs). They are considered to be a necessity if complex environmental decision making is to be adequately addressed (Matthies, Giupponi, & Ostendorf 2007). Yet while there is much enthusiasm for DSSs, they have failed to be used to their full potential, perhaps due to their lack of transparency, inflexibility, and technical nature (Jakeman & Letcher 2003). It is generally assumed that if these barriers are overcome and DSSs were actually used to implement ICM, decision making would be improved.

The last major barrier to the implementation of ICM is the large quantity of resources it requires. Bringing together all the relevant institutions, experts and stakeholders into the decision making process is extremely time consuming and laborious (Borowski & Hare 2007). Building all the models that encompass all the criteria, and then integrating them into a DSS is a complex, expensive, and again time consuming task (Lerner *et al.* 2011). What's more, DSSs will often be specific to a problem e.g. when dealing with weir modification (Jakeman & Letcher 2003), multiple systems will need to be produced to address the different catchment management issues that need dealing with.

1.3 Thesis overview

In this thesis work is presented that attempts to answer some of the questions raised above relevant to the management of weirs. Firstly a holistic framework of criteria for evaluating weir modification options is assembled using ecosystem services (ESs). The effect of weir modification on these criteria needs to be predicted if they are to be used to assess different management options. It is recognised that predicting sociocultural ESs poses a particular challenge, so the utility of Bayesian Networks (BNs) for dealing with these is explored.
An approach to deal with the interaction of multiple spatially separated weir modifications is then developed. To allow decision makers to plan weir modification at a catchment scale and to manage the models they are integrated into a DSS dubbed the Weir Tool. This is then used to test the basic assumption that the use of DSSs leads to improved decision making. The research questions of the thesis are stated and expanded on below.

1.3.1 Research questions

Research question 1. Can river provisioned ecosystem services form an evaluatory framework of criteria with which weir modifications should be assessed?

Ecosystem services (ES) are promoted as the framework with which environmental management options should be assessed. The holism of ESs makes the concept particularly attractive for conducting the ICM of weirs with. However questions exist as to whether the concept of ES can be operationalised, and just how suitable the framework is for use in evaluating catchment management scenarios. In chapter 2, a typology of ecosystem services is developed that can be used as a framework with which alternate weir modification options can be assessed. A number of questions are looked at including:

- whether existing ES typologies can be used as evaluatory criteria for the management of weirs?
- what ESs are affected by weir modification?
- have any of these ES not traditionally been considered during decision making?
- how practical is the ES concept to implement?
- is the ES framework complete or are any other criteria that should be included missed out?

Research question 2. Can a Bayesian Network be used to model sociocultural stakeholder interests?

A large proportion of the value rivers have is composed of intangible sociocultural ESs. This poses a big challenge to the implementation of holistic approached to environmental management, as their qualitative and subjective nature means they cannot be modelled using conventional approaches. In chapter 3, a model is introduced that predicts one such sociocultural ecosystem service, that danger posed and the fun provided by weirs to canoeists. This was achieved using a Bayesian Network (BN), chosen because it is able to mathematically describe relationships between variables for which the exact mechanism is not known.

Research question 3. How can weir modifications to improve river connectivity be modelled?

The effect of weirs on river connectivity is of major interests to weir modification decision makers. However it also poses another major difficulty, as to consider how weir modification affects connectivity, the strong interdependence multiple management interventions can have must be considered. Chapter 4 presents an approach that accounts for how multiple weir modifications can interact to have a synergistic impact on habitat accessibility for the European eel (*Anguilla anguilla*), Atlantic salmon (*Salmo salar*), the white-clawed crayfish (*Austropotamobius pallipes*) and the signal crayfish (*Pacifastacus leniusculus*). Potential outcomes of alternative strategies to open up the Don Catchment for these species are then compared, and implications to fish passage improvements are discussed.

Research question 4. Does the DSS tool produced to aid weir management decision making lead to improved decision making?

A web-based DSS named the Weir Tool was built to help decision makers handle the models so that they can plan weir modification at a catchment scale. Integrated into the DSS were the canoeing BN and the habitat accessibility models introduced in chapters 3 and 4, as well as a hydropower model and the weir modification costings described in appendix a. Details and discussion of the construction of the Weir Tool are presented in chapter 5. Many such DSSs built to aid decision making are not adopted and applied to real weir modification problems once they are built (Jakeman & Letcher 2003). A number of barriers have been identified as to why this is the case with it generally being assumed that if these barriers are overcome, then usage of DSS will result in improved decision making. In chapter 6, the results of a controlled experiment that was designed to test whether the Weir Tool resulted in improved decision making are presented.

Lastly chapter 7 presents the original contribution of the research described in this thesis, draws together its conclusions, and points out important future directions of research. The structure of the thesis is shown in Figure 1.7.

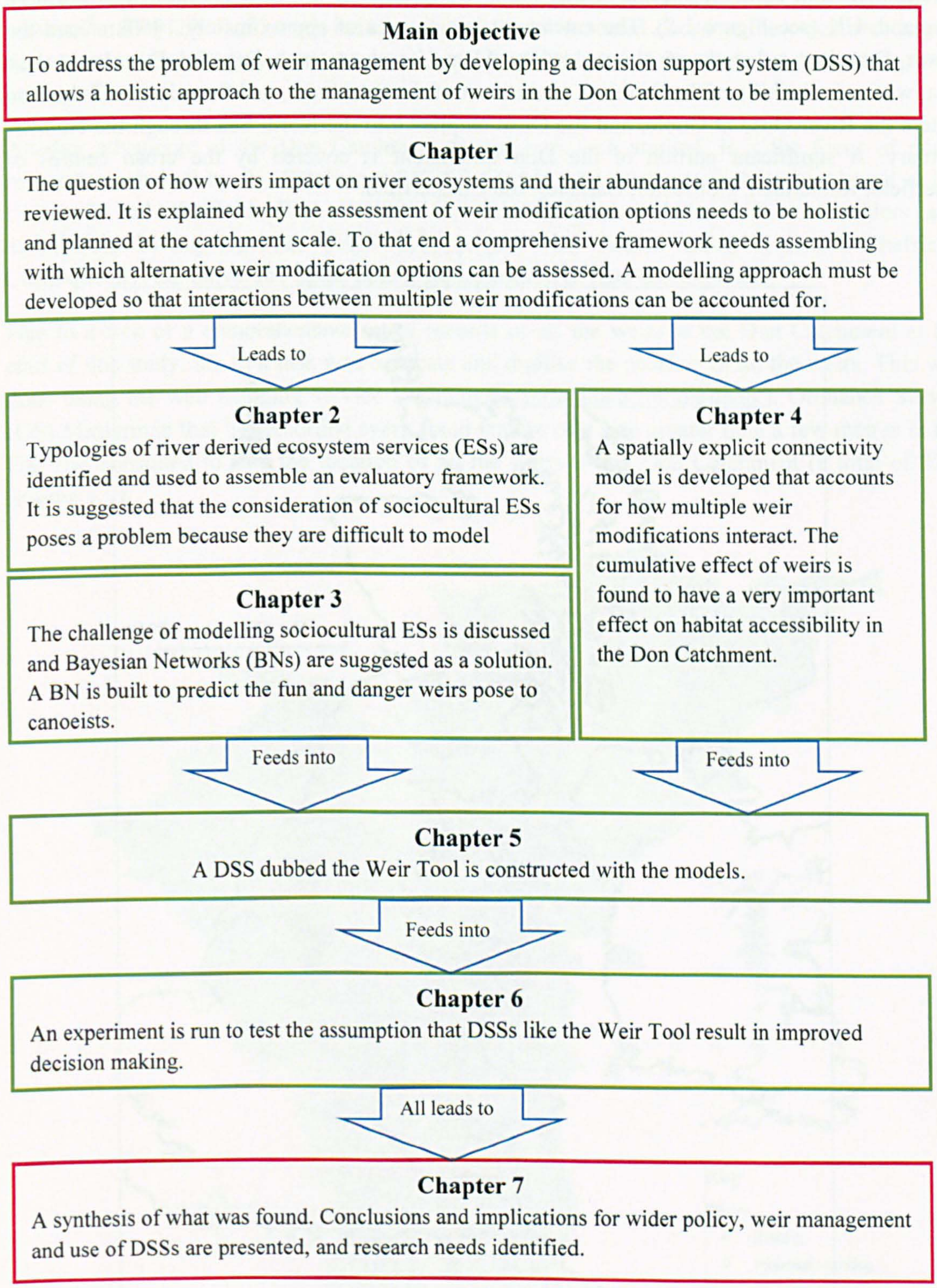


Figure 1.7. Flow chart showing the structure of the thesis.

1.3.2 Study catchment

The models and DSS introduced in this thesis were built for the Don Catchment in northern England, UK (see Figure 1.8). The catchment has an area of approximately 1800km^2 and the River Don has a length of about 110km. Many its rivers including the Don have their headwaters in the hills of the Pennines to the west of the catchment, and flow east until the Don enters the River Ouse at Goole, and the Ouse empties into the North Sea through the Humber Estuary. A significant portion of the Don Catchment is covered by the urban centres of Sheffield, Rotherham, Doncaster, Barnsley and Chesterfield.

Figure 1.8. Location of the Don Catchment within the British Isles.

Historically the catchment has hosted much heavy industry and a large attendant population that produced so much pollution that many of its rivers were almost lifeless for much of the last century (Firth 1997). The industrial past in the catchment is what makes it a good case study, as up until the technology was superseded, the Don Catchment had a high concentration of watermills (Hey 2005). Though industry has declined in recent decades, the catchment is still densely populated, and as a consequence has a large and varied number of stakeholder groups interested in its rivers.

Another advantage of the Don Catchment is that it is well studied. It is the focus of much research conducted by the Catchment Science Centre, and other research groups based at the University of Sheffield. For example, the interdisciplinary Urban River Corridors and Sustainable Living Agendas (URSULA) project has studied urban rivers in Sheffield. Consequently, the university holds both a concentration of data and expertise.

Due to a lack of a comprehensive set of records of all the weirs in the Don Catchment at the start of this study, the first task was to locate and digitise the position of all the weirs. This was done using the web mapping service Digimap (http://edina.ac.uk/digimap/). Ordnance Survey (OS) Mastermap that has recorded every fixed feature of a size greater than a few metres in the UK was consulted to find the location of all the weirs in the Don Catchment (a total of 229) (Figure 1.9).

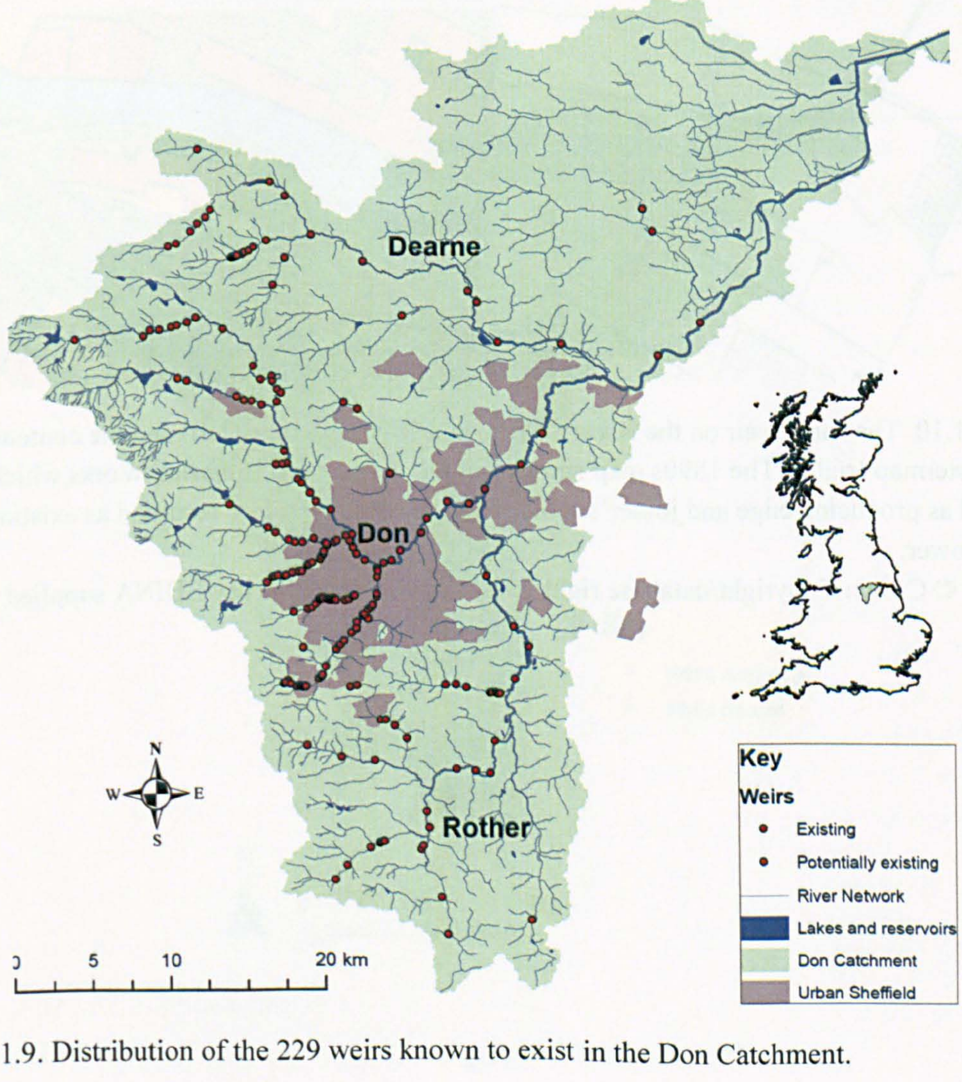


Figure 1.9. Distribution of the 229 weirs known to exist in the Don Catchment.

In addition, Digimap's collection of OS maps from between the 1840s and 1900, of a scale of either 1:500, 1:1056 or 1:2500 were consulted, and the presence and purpose of existence of the weirs were recorded to see how impoundment by weirs has changed over the last couple of centuries. The reason a weir was built could be inferred if there was an associated water mill or navigation was marked on the map (e.g. see Figure 1.10), though such clues were not always present. It is likely that the numbers of weirs in existence between the 1840s and 1900 were under recorded during this process, as some of the small weirs on the 1:2500 maps were hard to make out. However, the idea of this task was to provide a rough picture of how weir impoundment had changed through time.

It was found that there has been a reduction in the number of weirs between the 19th and the 21st centuries, with a loss of 77 of the 251 weirs that were originally present. Mainly former mill weirs were lost (see Figure 1.11). However, the total loss of weirs has been minimal as 55 new weirs have also been built (see Figure 1.12). In contrast to the weirs that have been lost, the new weirs are primarily concentrated on relatively short stretches of smaller rivers and are of a more moderate size. It is not known to the author why these new weirs were constructed, though because of their urban locations it could be to prevent river erosion and consequent bank instability.

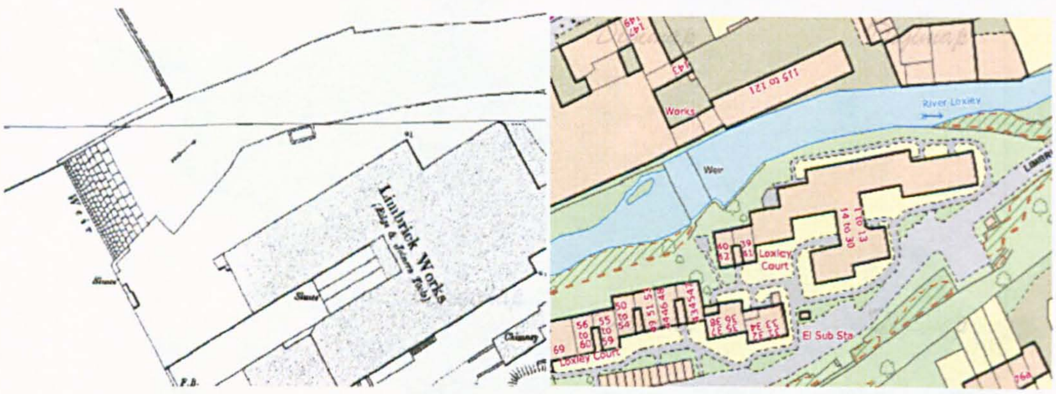


Figure 1.10. The same weir on the River Loxley in a 1890s OS map (left) and the contemporary OS Mastermap (right). The 1890s map shows that the weir served Limbrick Works which is labelled as producing edge and joiner's tools. This weir was therefore recorded as existing for water power.
Source: © Crown Copyright/database right 2011. An Ordnance Survey/EDINA supplied service

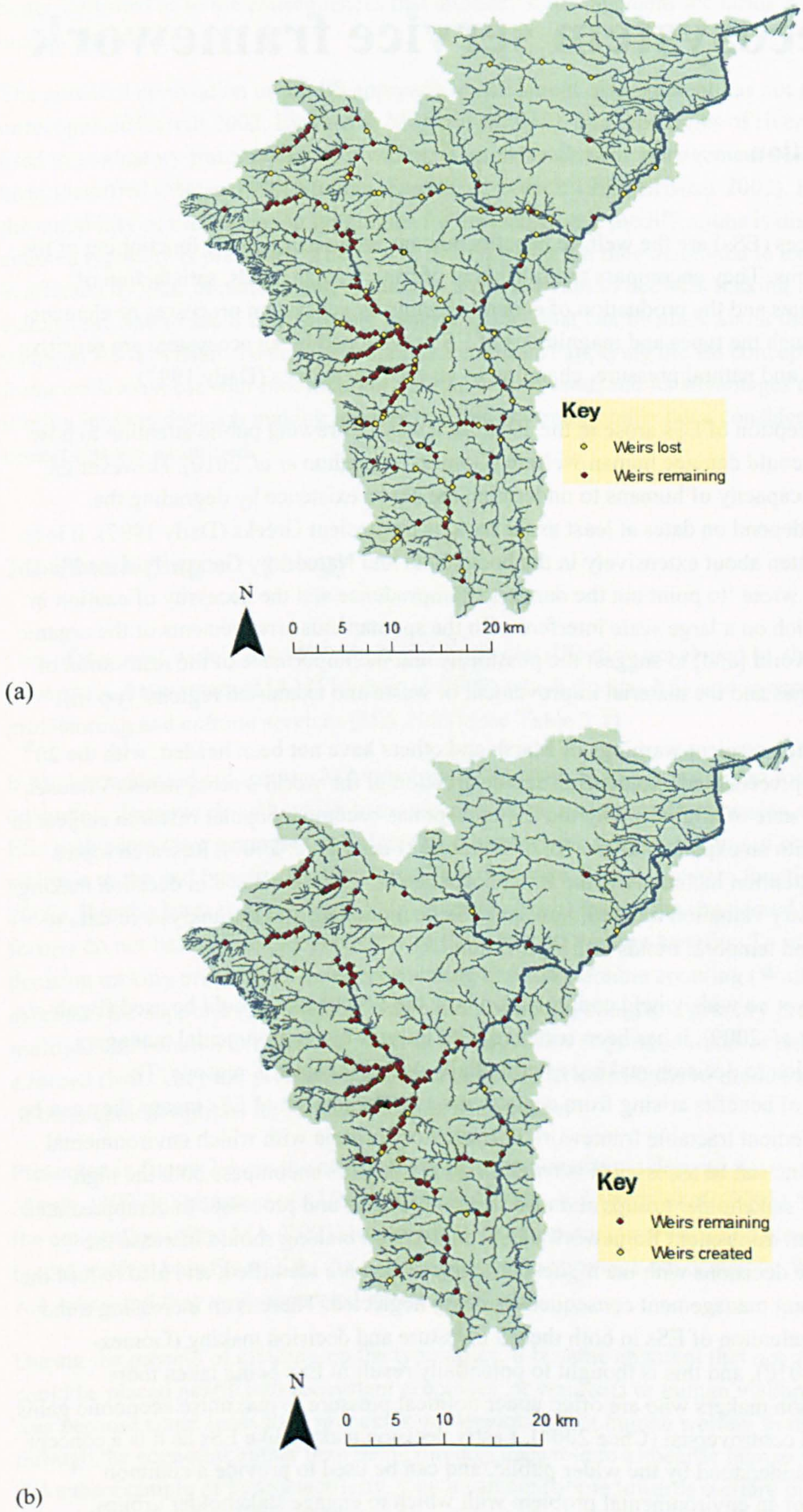


Figure 1.11. Weirs that have been lost (a) and gained (b) since the 19th century.

2 An ecosystem service framework

2.1 Introduction

Ecosystem services (ESs) are the welfare benefits humans receive due to the functioning of the world's ecosystems. They encompass the fulfilment of basic human needs, satisfaction of sociocultural values and the production of economic gains by ecosystem processes or elements (MA 2003). As such the types and magnitudes of ES provisioned by an ecosystem are sensitive to anthropogenic and natural pressure, changing as an ecosystem does (Daily 1997).

The modern conception of ESs arose in the 1970s as a way of drawing public attention to how biodiversity loss could damage human welfare (Gómez-Baggethun *et al.* 2010). However an awareness of the capacity of humans to undermine their own existence by degrading the ecosystems they depend on dates at least as far back as the ancient Greeks (Daily 1997). It is an idea that was written about extensively in the book 'Man and Nature' by George Perkins Marsh (1865), which he wrote 'to point out the dangers of imprudence and the necessity of caution in all operations which on a large scale interfere with the spontaneous arrangements of the organic or the inorganic world [and] to suggest the possibility and the importance of the restoration of disturbed harmonies and the material improvement of waste and exhausted regions' (pp iii).

Needless to say the prescient warnings of Marsh and others have not been heeded, with the 20th century seeing unprecedented exploitation and destruction of the world's ecosystems (Vitousek *et al.* 1997). This state of affairs is why the ES concept has become a popular research subject in recent decades, with an exponential growth of literature (Fisher *et al.* 2009). Research topics receiving much attention include how the ES concept can be operationalised in decision making e.g. should monetary valuation be used, how can ESs be modelled, and the analysis of data to examine spatial and temporal trends in ES provision.

While there is as yet no widely held consensus on how the ES concept should be used (Egoh *et al.* 2007; Fisher *et al.* 2009), it has been received with interest by environmental managers, seeing its application to decision making as potentially useful for several reasons. The conceptualisation of benefits arising from ecosystems as a discrete set of ESs means they can be turned into a convenient tractable framework of evaluatory criteria with which environmental management options can be assessed (Fisher *et al.* 2009). As ESs encompass both the high profile interests of stakeholder groups and also natural products and processes underappreciated by society, using an assessment framework of ESs in decision making should increase the probability that the decisions with the highest utilitarian value are identified, and also reduce the chances of important management consequences being neglected. There is an increasing trend for the monetary valuation of ESs in both the ES literature and decision making (Gómez-Baggethun *et al.* 2010), and this is thought to potentially result in ESs being taken more seriously by decision makers who are often under political pressure to maximise economic gains, though the topic is controversial (Chee 2004). Lastly decision makers like ESs as it is a concept that can easily be understood by the wider public, and can be used to provide a common conceptualisation of an environmental problem with which to engage stakeholder groups. Stakeholders are therefore less likely to be alienated by technical or abstract notions and are better informed as to the consequences that alternative management scenarios will have for human welfare.

The potential application of the ES approach in catchment management has not gone unrecognised (Jewitt 2002; Everard & Moggridge 2011), and typologies of river ESs that can be used as evaluatory frameworks with which to assess catchment management scenarios have been identified (Meyer 1997; Strange, Fausch, & Covich 1999; Brismar 2002). In this chapter, the suitability of these existing typologies for assessing weir modifications is discussed and an adapted typology is presented. The ESs in this typology are then examined to explore how each is affected by weir impoundment, to identify those relevant to decision making in the Don Catchment, and to see if there are any generalisations that can be made about the impact of weirs on ES provision. To conclude the practicalities of applying the ES concept as a framework to assess weir modification options is discussed, and its advantages e.g. what would it bring into the decision making process that has not traditionally been considered, and limitations are examined.

2.2 Developing a typology

One of the most widely used ES typologies is the classification developed by the Millennium Ecosystem Assessment (MA) (Fisher *et al.* 2009) which divides ESs into supporting, regulating, provisioning and cultural services (MA 2003) (see Table 2.1).

It has been pointed out that the MA typology of ecosystem ESs is not suited for use as a evaluatory framework with which to assess alternative management scenarios, as it includes as ESs both ecosystem processes and elements necessary for the functioning of ecosystems, in addition to the end benefits for human welfare that arise from ecosystem functioning (Wallace 2007). It is the latter that Wallace (2007) suggest should instead be considered as ESs, as the former do not have value independently of these human welfare benefits. To include both in the decision making process can be overwhelming and risks double counting (Wallace 2007). For example, the supporting services of water and nutrient cycling, and primary production underlie multiple end benefits to humanity, such as the provision of potable water or fish, or the flow of a sacred river. They are processes that need to be modelled in order to predict the implications of management options for human interests i.e. the ESs.

Presented in figure 2.1 are the amalgamated typologies of river derived ecosystem services of Meyer, (1997), Strange *et al.* (1999), Brismar (2002), and Ojeda *et al.* (2008). All have followed the convention of the MA (2003) to include both ecosystem processes and elements in addition to end welfare benefits as ESs. As a consequence the approach advocated by Wallace (2007) was taken and they were separated into these groups.

During the process of dividing up the typologies, it became apparent that not all of the ESs could be placed neatly into ecosystem processes, or elements or human welfare benefits. This was because some ecosystem processes or elements affect human welfare in multiple ways through the economy, rather than being directly traceable to a specific human welfare interest. Take the example of hydroelectricity, which can contribute towards welfare in a myriad of ways of varying importance; street lighting for safety, heaters for shelter, machinery for processing

Table 2.1. The ecosystem service typology identified by the Millennium Ecosystem Assessment (2005).

Category of service	Ecosystem service
Provisioning *(The goods or products obtained from ecosystem)*	Food Fibre Genetic resources Bio-chemicals, natural medicines, etc. Ornamental resources Fresh water
Regulating *(The benefits obtained from an ecosystem's control of natural processes)*	Air quality regulation Climate regulation Water regulation Erosion regulation Disease regulation Pest regulation Pollination Natural hazard regulation
Cultural *(The nonmaterial benefits obtained from ecosystems)*	Cultural diversity Spiritual and religious values Knowledge systems Educational values Inspiration Aesthetic values Social relations Sense of place Cultural heritage values Recreation and ecotourism
Supporting services *(The natural processes that maintain the other ecosystem services)*	Soil formation Photosynthesis Primary production Nutrient cycling Water cycling

food and water, televisions for entertainment etc. Therefore, as well as including direct welfare benefits as ESs (Figure 2.1b), for practical reasons the suggested typology also includes the effects an ecosystem has on the economy as a separate set of ecosystem services (Figure 2.1c). It is left to decision makers to consider how important these are to human welfare.

2.3 The impact of weirs on river ecosystem services

The ES typology presented in figure 2.1 includes all the ESs that a river potentially can provision. This new typology differs from the existing ones by discriminating between ecosystem processes and human welfare benefits and omitting the former. The distinction is important as the latter are more appropriate for use as a framework with which to assess alternative ecosystem management options. They form a set of criteria that have independent value in contributing towards human welfare, and so the use of this typology avoids the problem of double counting, a frequent issue in ES accounting studies (Fu *et al.* 2011). This makes the application of the ES approach more practical and more credible to stakeholders and decision makers, important research priorities as global ES provision continues to be eroded (MA 2005).

Weirs may not necessarily affect all ecosystem services identified in the typology. Fewer still will be influenced by weir modification in the Don Catchment. To identify which of the ESs are relevant to weir modification, each is reviewed, and a framework of ESs is assembled that should be used to evaluate weir modification scenarios in the Don Catchment.

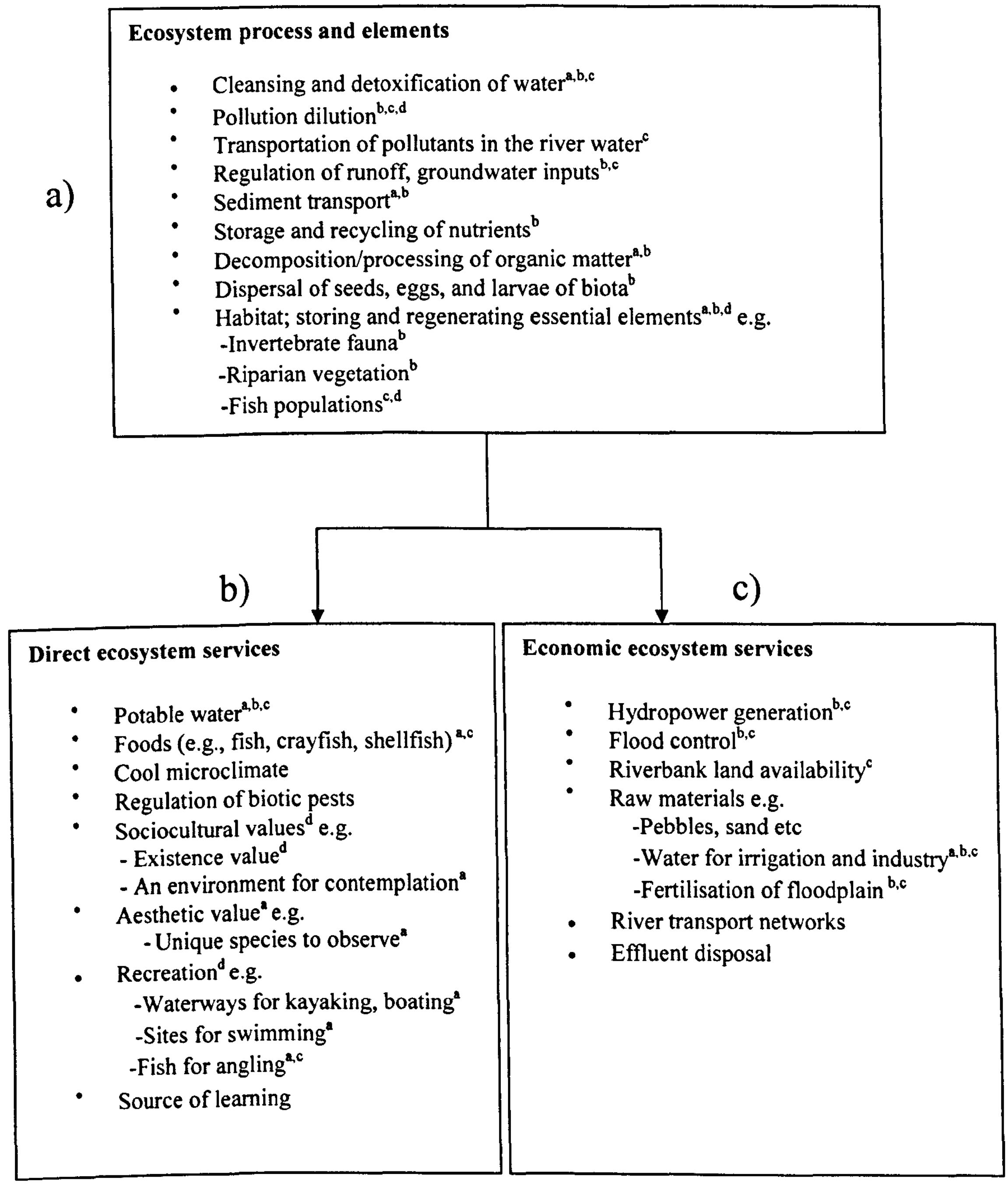


Figure 2.1. River ecosystem services divided into those which are underpinning ecosystem processes and elements that compose the river ecosystem (a) and those which correspond to specific human benefits and are therefore more tractable for ecosystem service accounting (b and c). [a]Meyer (1997); [b]Strange *et al.* (1999); [c]Brismar 2002; [d]Ojeda *et al.* (2008).

2.3.1 Direct ecosystem services

Potable water

Weirs can affect both the quantity of drinking water provisioned by a river and its quality. Firstly, the presence of water available for drinking in temporary rivers is prolonged by storage in weir pools. This also allows greater recharge of groundwater, and for this reason weir construction is a strategy to help recharge depleted groundwater in parts of India (UNEP 1999). Secondly, weirs can influence the abundance of the pathogens through modification of the river ecosystem (see Regulation of pathogens) and the concentrations of harmful chemicals through both the aeration of river water (Novotny 2003) and by impeding the transport of contaminated sediments (Lenczowska-Baranek 1996). With many potential contaminants with unique ecosystem interactions or chemical pathways, it is not possible to draw generalisations on how they are affected by weir modification, and so this must be done on a case by case basis. Consequently, this ecosystem service should be considered in some catchments, though in the case of the Don Catchment, water is taken from reservoirs in the headwaters where there are few weirs, and so is not relevant.

Foods

Many people around the world, particularly in developing countries, depend on rivers to provide a source of food (Neiland & Béné 2006). As discussed in chapter 1, important food resources such as fish, macroinvertebrates, and bivalves are frequently impacted by weirs. The effect is species specific, for example, weirs are often detrimental to stocks of Atlantic salmon (*Salmo salar*) (de Leaniz 2008) but can be beneficial to *Tilapia* spp (FAO 1966), and so the effect cannot be generalised. In the rivers of the Don Catchment, there is no commercial extraction of food resources and this ecosystem service would not form part of the evaluatory framework.

Cool microclimate in hot conditions

Water reduces air temperature through evaporative cooling, and several studies have shown water bodies such as rivers to cool the surrounding air (Murakawa *et al.* 1991; Nishimura *et al.* 1998). Murakawa *et al.* (1991) found that on hot summer days the edges of a 100m wide river in a Japanese city were 3°C cooler than surrounding areas. This cooling effect, positively correlated with air temperature, can create a microclimate adjacent to rivers more comfortable for humans. Not only does this directly benefit those who enjoy the cooler temperatures, but it indirectly has economic benefits by reducing usage of air-conditioning in riverside buildings. Weirs influence the cooling effect by widening the river and creating spray, thereby increasing evaporative cooling. In the Don Catchment, this ecosystem service is likely to exist, but not to be significant as all rivers are small and air temperatures infrequently become uncomfortably hot in the region (Average summer temperature approximately 14-15 °C (Met Office 2008)).

Regulation of pathogens

With some of the world's most dangerous diseases dependent on water bodies for their transmission, the effect of weir modification on the occurrence of human pathogens should be a serious consideration in many places around the globe. For example Malaria, infecting hundreds of millions and killing nearly 800,000 people in 2009 (Aregawi *et al.* 2010), is spread by mosquitoes that spend their larval stages in freshwater. The mosquito vectors profit from the lentic conditions upstream of impoundments (Meade, Florin, & Gesler 1988), and so weirs can increase the occurrence of the disease. Schistosoma spp., trematode flatworms that take humans as hosts in their final stage of their life-cycle, are another of the world's most serious diseases, estimated to have infected 200 million people, and annually causing the death of 200,000 (WHO 2010). The parasite has seen large increases in abundance in regions where weir impoundment for irrigation is common because the lentic conditions favour their intermediate hosts, freshwater snails (Meade *et al.* 1988). Other diseases that have increased due to river impoundment include lymphatic philariasis, encephalitis and clonorchiasis (Meade *et al.* 1988).

Impoundment of rivers by weirs does not always necessarily favour diseases as it depends on the ecology of the disease organism. River blindness (onchocerciasis) has decreased in South Africa as weir impoundment has reduced the quantity of fast flowing habitats required by its black fly (Simuliidae) vector (Meade *et al.* 1988).

In the Don Catchment there are currently no significant diseases that are affected by weir modification. This could change in the near future as globalisation and global warming facilitates the spread of mosquito-borne diseases into new areas (Feresin 2007), though developed countries are more able to deal with outbreaks of such diseases.

Sociocultural values

The ecosystem services of satisfaction of sociocultural values are somewhat inseparable from aesthetic and recreational values, with cultural values influencing a recreational or aesthetic experience. Putting value on rarity might mean that spotting a rare species enhances a walk, or putting value on traditional landscape management practices might mean we find landscapes that are so managed to be more aesthetically pleasing. Yet all three ecosystem services can be independent; it is not necessary to directly experience an ecosystem element or process, such as a polar bear, to value its existence, and even if we were never exposed to culture, we would still have an innate evolved sense of aesthetics (Kaplan 1987). For this reason the three types of ecosystem service are dealt with separately.

Being intangible, sociocultural values are not easily defined and classified for the purposes of ecosystem service accounting (Wallace 2007). In general they can be said to be non-utilitarian values attached to an actual or perceived state of an ecosystem entity (e.g. the existence of kingfishers), process (e.g. seasonal migrations) or associated abstract concept (e.g. biodiversity). Sociocultural values are products of the cultural environment, existing within the medium of the human mind, and are based on conceptions of nature arising from ethical, religious, cultural or philosophical viewpoints (MA 2005). As the human brain is the product of evolution, they have been to some degree shaped by natural selection. The fact that the concept of non-utilitarian values is found in cultures as diverse as the indigenous societies of North and South America, Africa and Australia as well as the major religious traditions of Europe, the Middle-East and

Asia (Millennium Ecosystem Assessment 2005) suggests that these values are a fundamental aspect of human society.

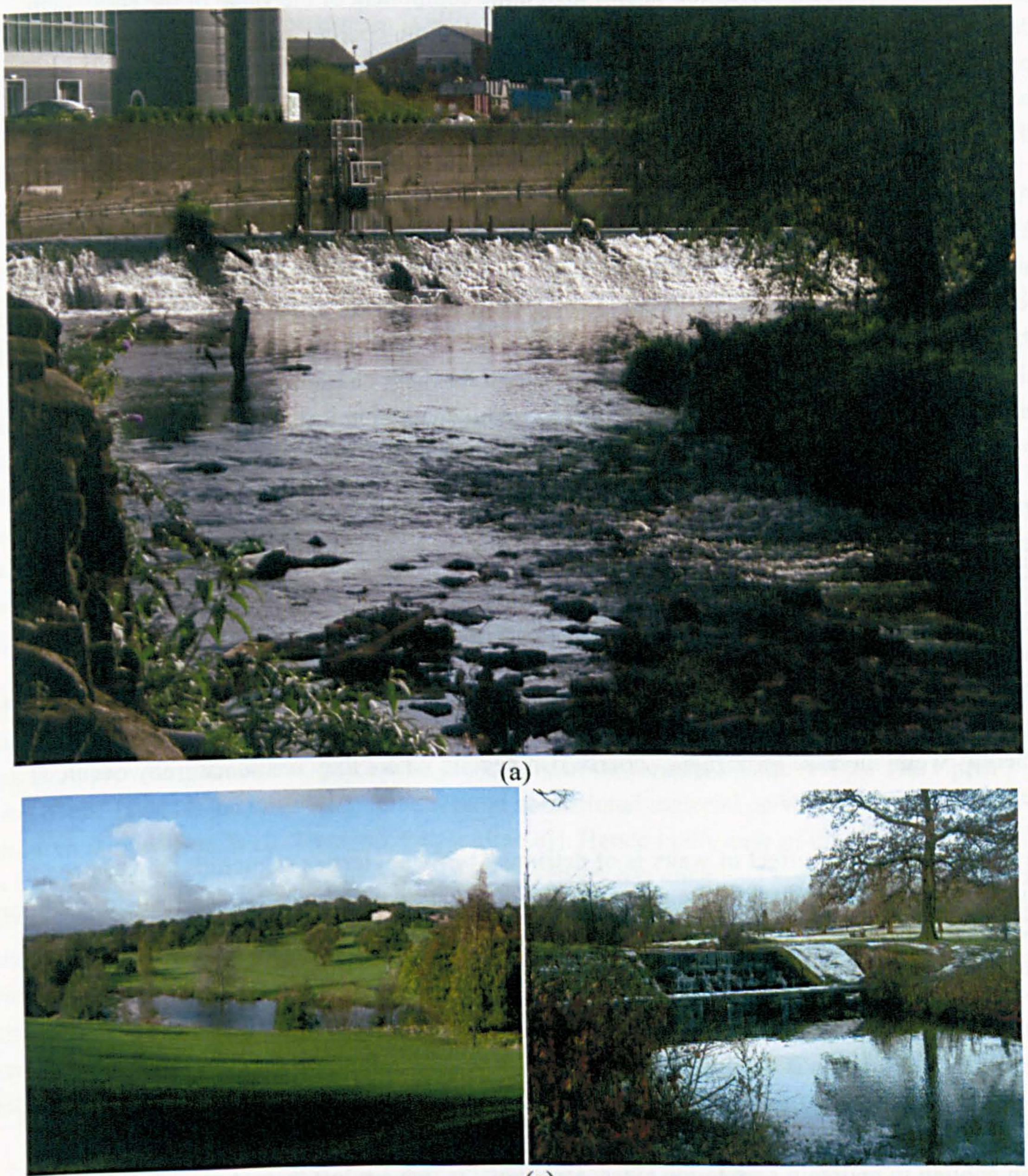
As sociocultural values encompass potentially any aspect of any ecosystem, with each sentient individual on earth holding their own unique set, the range is vast. However, for the purposes of ecosystem service accounting, it is perhaps the case that there are a common set of values shared by many people worldwide due to an innate affinity with nature, famously termed by E.O. Wilson (1984) as 'biophilia'. Generally these are based around concepts attached to ecosystems including uniqueness, rarity, naturalness, diversity and health (Wilson 1984). For example, in the Don Catchment, the Sheffield Wildlife Trust (2008) produced an action plan for the River Don that seeks to conserve or enhance rare or threatened habitats and species, biodiversity, and natural ecosystems.

The strong impact of weirs on river ecosystems means that it is almost certain that in most catchments they will affect some sociocultural values attached to river ecosystems. There are many examples of sociocultural values driving conservation work within the Don Catchment, including the installation of eel passes on weirs to aid conservation of the critically endangered European eel (*Anguilla anguilla*) and preserving weirs where they act as a barrier to the invasive signal crayfish (*Pacifastacus leniusculus*) which is threatening the native white-clawed crayfish (*Austropotamobius pallipes*).

Of course cultural values are not restricted to the natural components of the ecosystem, but also apply to the made environment. There have been weirs in the Don Catchment for over 700 years which have played an important role in the development of the region (Hey 2005), and as a consequence are valued for their heritage. Indeed several weirs have listed status, affording them some degree of protection from modification. In China, the historical value of a huge weir built in 252BC at Dujiangyan to provide irrigation to the Sichuan Basin has been recognised through designation as a UNESCO World Heritage site (China Heritage Project 2005). Though strictly speaking heritage value of the made environment is not an ES, it is in within the holistic spirit of the ES concept to include it within an evaluatory framework.

Aesthetics

The presence of a water body in a landscape is widely believed to enhance its visual attractiveness, though to what degree is determined by its characteristics (Burmil, Daniel, & Hetherington 1999). What humans perceive as attractive is partly a product of evolutionary hard wiring (Kaplan 1987), but it is also shaped by our environmental and cultural conditioning, and so it is not possible to generalise the overall aesthetic impact of weirs on landscape aesthetics. However it is likely to be important, as weirs can have a big impact on the appearance of rivers. River reaches upstream of weirs can look more like canals with flat, placid water (e.g. see Figure 2.2a), and the cascade of water over the weir itself can be quite striking, both reasons why weirs have been employed in landscape design. For example, the famous Georgian landscape architect Capability Brown included weirs as part of his designs of parks and gardens. Today weirs are commonly found in such places. For instance, in the Don Catchment, weirs have been used to produce ponds in the grounds of Bretton Hall and Cannon Hall (see Figures 2.2 b & c). Wherever landscape aesthetics is of interest to stakeholders, such as in the Don Catchment, then this ES should be part of an evaluatory framework.



(a)

(b) (c)

Figure 2.2. (a) Brightside Weir on the River Don. The Don upstream and downstream of the weir is visually quite different. Upstream is like a canal, with an even water level, whereas downstream the river is more like an upland river. (b) The dammed Cawthorne Dyke in the grounds of Cannon Hall[1] and (c) the weir that produces the weir pond[2].
[1]*Source*: http://northernstock.web.officelive.com/outabout.aspx
[2]*Source*: http://www.yourlocalweb.co.uk/south-yorkshire/cawthorne/pictures/

Recreation

Globally rivers are important sites of recreation. Some recreational activities are directly dependent on rivers which will be discussed next. Other activities are enhanced by the aesthetic and sociocultural values rivers provide (discussed above), but do not require a river to be undertaken (e.g. walking). Major worldwide recreational activities directly dependent on rivers include canoeing, boating, swimming and fishing, all of which are affected by weir modification.

In the Don Catchment recreation makes up a large component of the value of the ecosystem services provided by the rivers, with two types of angling, boating and canoeing being particularly popular. The heritage value of the rivers, derived from the central role they have had in shaping local history, is also a draw for many types of recreation. Therefore these interests must form part of the evaluatory framework.

As a large proportion of the weirs in the Don Catchment were built as part of watermill infrastructure and date back many hundreds of years, to many people they hold considerable heritage value. To those river users who appreciate this heritage value, weirs can enhance the recreational value of the rivers. In the Don Catchment weirs are celebrated by the local charities the Five Weirs Walk Trust and the Upper Don Walk Trust which have established public access along sections of the river. An important objective for these charities is to enable people to undertake recreational activities along the river whilst enjoying its heritage features such as the weirs (Five Weirs Walk Trust, no date [online], Upper Don Walk Trust, no date [online a]).

In addition to indirectly enhancing recreation activities, weirs can also directly affect recreational activities. They influence the value of a river for fishing due to the strong impact they can have on the fish community. In the Don Catchment, two types of angling are affected by weirs; coarse anglers, (the majority) who target 'coarse' fish that occur in relatively lentic habitats, and fly anglers who target salmonids such as brown trout (*Salmo trutta*) that occur in lotic habitats. The lentic conditions occurring upstream of weirs allow coarse fish populations to exist even in fast flowing rivers where they would not ordinarily occur (Firth, pers. com. 2008). Thereby weirs increase the range of coarse fish beyond where they would naturally occur, of benefit to coarse anglers.

In general the barrier effect of weirs is of detriment to fly anglers as salmonids tend to need to migrate long distances to spawn e.g. sea trout (*Salmo trutta* morpha *trutta*), and Atlantic salmon (*Salmo salar*).These species have high angling value to fly anglers and are prevented by weirs from reaching spawning grounds in the Don Catchment.

On the face of it there appears to be a conflict between the interests of coarse and fly anglers. However the situation is complicated by the small fragmented nature of the populations of coarse fish upstream of weirs which have often developed through stocking or been washed in from other waterbodies. Due to their small size and isolation, natural recruitment may not be high enough to maintain population sizes, especially as fish are lost from these populations during times of spate and are obstructed from returning by weirs (Firth pers. com. 2008). If this is the case then restocking will need to occur permanently if the populations are to be maintained. Installation of fish passes could mitigate fragmentation by allowing longitudinal movement of fish, though it is not known whether connectivity would be increased enough to result in sustainable populations.

Weirs may sometimes have a positive effect on fish populations by oxygenating rivers. Influxes of organic matter into a river combined with hot weather can result in a rapid increase in BOD, causing hypoxic conditions and fish kills; an occasional problem in the Don Catchment. An influx of sewage during hot weather in the summer of 2007 resulted in a large fish kill downstream of Sheffield, culminating with the Environment Agency having to restock fish (Environment Agency 2007a). In such events the oxygenated reaches downstream of a weir serve may serve as a refuge for fish (Firth 1997).

Interviews with canoe groups in the Don Catchment have revealed the effect of weirs on canoeing quality within the catchment is also complicated. Weirs pose both a hazard and also an object of fun for canoeists. The physical forces involved in chuting (descending) a weir can cause injury, and under certain circumstances the circulating currents underwater below a weir can pose serious drowning risks. Yet the same weir attributes such as height, slope, flow volume, that determine hazard risk also determine how exciting a weir is to chute.

Weirs are also important in the Don Catchment to people who use narrow boats. Some weirs are important infrastructure that are essential in maintaining the water levels both within the canals, and within navigable stretches of the Don itself. These weirs are amongst the biggest within the catchment due to their role in creating navigable water depths.

Source of learning

Learning and knowledge creation processes such as science depend largely on the physical world as a resource for observation and evidence gathering. Knowledge gained has value for two reasons; it allows humans to interact with and influence the world in a way that is beneficial to our welfare, and it satisfies our innate desire for knowledge. For this reason weirs have value as objects of study, as sources of curiosity and as visual aids that stimulate learning.

In the Don Catchment this is again reflected by the Five Weirs Walk Trust and the Upper Don Walk Trust. The former have published a guidebook that introduces the heritage of a stretch of the Don, providing much information on the history of its weirs (Griffiths 1999). The Upper Don Walk Trust on the other hand have created educational material on weirs for school children (Upper Don Walk Trust, no date [online b]). Hence in the case of the Don Catchment it is conceivable that the presence of weirs along the rivers has enhanced knowledge of the area's history for those who have wondered about them. The influence of the environmental variation created by the weirs on the river ecosystem is also being studied at the University of Sheffield. However, the converse could also be argued; that weirs are inhibiting the production of knowledge about the things they are preventing, such as the return of Atlantic salmon to the catchment. Therefore an evaluatory framework should consider how weirs might both positively and negatively affect knowledge and learning opportunities.

2.3.2 Economic ecosystem services

Hydro power

The need for renewable energy has led to increasing interest across the UK in the installation of microhydro on weirs. The designs are based on the Archimedes screw, with the internal screw functioning as the turbine, which unlike conventional turbines, appears to do little damage to fish that pass through. A scoping study has been carried out for the weirs in Sheffield to assess the suitability for installation of microhydro (IT Power 2006). Of eleven weirs evaluated, eight were found suitable for microhydro. The annual yearly output of the microhydro, which can be calculated using the flow duration curve of the river, hydraulic head of the weir (height between the crest of the weir to the river level downstream), and microhydro specifications (see Appendix a), ranges from 256 MWh for Niagara Weir which provides the highest to 120MWh for Rocher Bridge Weir. If all suitable weirs identified in the IT Power report had microhydro installed the total annual output would be 1788 MWh, equivalent to the electricity needs of 457 Sheffield citizens (average annual electricity consumption of a Sheffield citizen is 3.912 MWh (BERR 2008)), or 0.086% of Sheffield's annual domestic energy needs. With much interest in exploiting the weirs for microhydro in the Don Catchment, this ecosystem service needs to be considered as part of the evaluator framework of ecosystem services.

Flood control

Flooding is directly responsible for harm to individuals and for substantial disturbance to human activity, indirectly harming human welfare. Weirs can influence flooding both negatively and positively. At the local scale, the weirs can exacerbate flooding by raising water levels and by collecting debris, both making flooding more likely upstream. But at a wider scale, by attenuating water, weirs may reduce flooding downstream, the effect potentially being cumulative when there are multiple weirs (Porter 2011). However, the effect is complicated and depends on the timings of flow. Flow attenuation can also make flooding worse; in a flashy river attenuation of flows can cause the synchronisation of the flood pulse with a less flashy river (Porter 2011).

The rivers in the Don Catchment periodically flood. During the summer of 2007 particularly severe flooding occurred resulting in two fatalities and £30m of damage (BBC 2008), and so flooding must be part of the evaluatory framework

Riverbank land availability

Sediment loads and flow regimes of rivers determine where and by how much erosion and formation of new land occurs. Weir construction results in a wider river and loss of riparian land. For example the river Don in Sheffield can be up to 90m wide by weirs whereas unimpounded sections are typically about 20m wide. Hence where weirs are created or removed there can be a significant change in land availability.

Weirs also prevent erosion by concentrating height loss of the upstream river reach at the point where the water cascades over the weir. The erosive energy of the river can then be dissipated in a controlled manner. Small weirs built to prevent the erosion of river banks are commonly found in urban areas. Without them, human activity on river banks are more likely to be disturbed. As the Don Catchment is highly urbanised, both of the effects of weirs on land use availability are significant to decision makers, and consequently must be considered in the decision making.

Raw materials

Substances derived from rivers include water for irrigation and industrial processes, sediment deposition on flood plains, and gravels and sand for construction etc. Weirs can have a role in extracting some of these materials. The primary function of many weirs in arid areas is to draw off water into a divergence channel for irrigation, a role that can be very important to the productivity of a region. The weir at Dujiangyan in China, referred to earlier, is credited in causing the Sichuan Basin to become one of the most productive and populous areas of China (China Heritage Project 2005).

The effect of weirs on the deposition of sediment on floodplains is not likely to be significant, as this occurs in floods of a scale that dwarfs the impact of weirs. Weirs are however used to trap substrate such as sand or gravel in the weir pond, so that after it has accumulated it can be conveniently extracted.

In the Don Catchment, only water is abstracted from the rivers, and while this was previously important for industry, especially for cooling, it is now only known to occur at a single weir. Therefore is not necessary to consider this ES in an evaluatory framework.

River navigation
As was mentioned above, weirs are used to maintain adequate water levels in rivers used as navigations. Rivers such as the Rhine and the Mississippi are major arteries for the transport of goods into the hearts of Europe and America. Shipping goods by boat is a particularly efficient method of transport, and so these rivers provide major economic benefits to the countries they service. The River Don canal and navigation was built in the industrial revolution, when canals were vital infrastructure that allowed the cheap conveyance of bulky materials such as iron ore or coal by narrow boat (Hey 2005). The canal and narrow boat system of transporting goods has declined due to the competition with railways and road network. It is therefore no longer significant in the Don Catchment. Though while it seems unlikely, it must be borne in mind that there is the possibility that due to its efficiency, the Don Navigation might potentially be used to transport goods again in the future. Therefore decision makers might want to consider this ES in the Don Catchment as something that can be bequeathed to the future.

Effluent disposal
One of the reasons rivers have become so degraded due to human activity is because they have been very useful as conduits through which to wastes could be disposed. The River Don used to receive large quantities of sewage, offal and by-products of the butchery, and all the effluents associated with the industry of Sheffield (Firth 1997). Still today, the Don serves Sheffield by taking its treated waste water and urban runoff. As was mentioned earlier, weirs can affect the capacity of rivers to transport pollution. However, this effect is likely too small to impinge on this ES.

2.4. Discussion and Conclusion

All but one of the entire set of river ESs in the typology assembled in this chapter are potentially affected by weirs (see Table 2.2). When making weir modification decisions, these ESs must be reviewed to identify whether they are relevant in the focus catchment, and those found to be so included in an evaluatory framework with which management options can be assessed. A large subset of these was found to be significant in the Don Catchment and therefore should be considered in decision making (see Table 2.2). One telling finding was that no provisioning ESs were relevant to weir modification decision making in the Don Catchment. This is because in developed countries such as those in Europe, many of the ESs people consume are imported from elsewhere. As the UK seeks to become more sustainable, and its river ecosystems recover

Table 2.2. How the typology of ecosystem services is likely to be affected by weirs, and whether they should form part of an evaluator framework with which weirs in the Don Catchment should be assessed.

Ecosystem services	Effect of weirs on service provision	Relevant in the Don Catchment?	Do weirs have an interdependent effect on provision?
Potable water	↓↑		✓
Foods	↓↑		✓
Cool microclimate	↑		
Regulation of biotic pests	↓↑		✓
Sociocultural values	↓↑	✓	✓
Aesthetic value	↓↑	✓	
Recreation	↓↑	✓	✓
Source of learning	↓↑	✓	✓
Hydropower generation	↑	✓	
Flood control	↓↑	✓	✓
Riverbank erosion control	↑	✓	✓
Raw materials	↑		✓
Rivers as transport networks	↑	✓?	✓
Effluent disposal	n/a		

from environmental degradation, it is possible provisioning services may become more significant in the future.

It is clear that the impact of weirs on river derived ESs is complex and generalisations cannot be made. For most, the effect of weirs on provision can be either positive or negative, depending on the social, economic and ecosystem context. For example, weirs can increase the extent of flooding in some areas and reduce it elsewhere, and benefit some species of conservation value e.g. the white-clawed crayfish and be detrimental to others e.g. the European eel. This is significant as river restoration and fisheries guidance can sometimes advocate a single type of management in response to weir impoundment. Kroes *et al.* (2006c), for example, in their European fisheries guidance advocate removing weirs whenever possible, a view that stems from the predominantly negative impact weirs have had on fish migration. Such a rigid stance should be avoided, and instead weir management should be done carefully and thoughtfully, considering all ESs in the decision making process.

The installation of fish passes and weir removals are measures that are expected to enable the UK to comply with the recently enacted European Union wide Water Framework Directive (WFD), which legally obliges the UK to achieve 'Good Ecological Status' (GES) i.e. slightly different from pristine ecological condition (EC 2000) for its rivers in the coming decades (Environment Agency 2009). It has been suggested that the objectives of the WFD can be justified by communicating to the general public in terms of ESs the benefits to society that will result from rivers with higher ecological statuses (Everard 2011). It should however be noted that ecological status does not correlate with the provision of all of the ESs that have been identified. Therefore interests of stakeholders and the WFD do not necessarily align. Nevertheless, the use of the ES typology would help clarify to the general public the pros and cons of achieving WFD objectives.

What is uncertain is whether weir removal will always help achieve WFD targets. The loss of river connectivity due to large weirs that impede fish populations will undoubtedly make it more likely that GES will not be achieved, as fish populations are one criterion which determines the ecological status of rivers. Less definite are the consequences of removing small weirs. In heavily urbanised and intensively managed catchments such as the Don, many rivers are resectioned and straightened, increasing the homogeneity of ecosystem processes. Small weirs on the other hand create greater heterogeneity at a reach scale within the catchment. They are analogous to some natural elements that are now lost or no longer allowed to develop

within the Don Catchment such as beaver dams, debris dams and bank collapses (Hart *et al.* 2002). Gravel shoals tend to form downstream of weirs, another feature that have been lost from many modified rivers (Tockner *et al.* 2003). It is easy to imagine that weirs could increase the overall diversity of a taxonomic group like macroinvertebrates within a river, thereby helping WFD targets be achieved. More research is required to understand how weirs impact on the feasibility of delivering the WFD objectives.

The WFD does not require all rivers to reach GES. A river can be classified as a heavily modified waterbody (HMWB) if by achieving GES (i) the wider environment; (ii) navigation, including port facilities, or recreation; (iii) activities for the purposes of which water is stored, such as drinking-water supply, power generation or irrigation; (iv) water regulation, flood protection, land drainage or (v) other equally important sustainable human development activities would be adversely affected. When a river is classified as heavily modified, 'mitigation measures' must be implemented so that it achieves 'Good Ecological Potential', meaning it is less than slightly different from its 'Maximum Ecological Potential', the best status that can be expected given society's needs. Clearly, the questions of whether a waterbody is a HMWB and whether it has achieved GEP are open to interpretation (Borja and Elliott 2007). To reduce this ambiguity, it may be possible to employ the ES typology presented in this chapter. Standards of ES provision could be set for river reaches, that if the attainment of GES results in that reach failing, then it should be classified as a HMWB i.e. it causes an unreasonable trade-off in ES provision. The typology could then be used as a framework for stakeholders to use in a collaborative environment to set targets of ES provision that must be met for GEP status to be achieved. This would bring some of the holistic benefits of the ES concept into the implementation of the WFD.

The ESs identified as being affected by weir modification did not throw up any surprises. It seems quite possible a decision maker not exposed to the ES concept who sought to produce a holistic evaluatory framework could come up with the same list of ESs themselves. No ESs emerged that are overlooked by the populace of the Don Catchment; most having stakeholder groups who will lobby for their provision. But one advantage of the ES typology is that it can provide a comprehensive structured framework that decision makers can be confident attempts to include all of the ESs they should be considering. In contrast, in the author's experience, weir modification decision making in the Don Catchment has been ad hoc, and does not typically consider more than a few of these ESs together during the planning stage, even when there has been awareness of more. Therefore there is an institutional failure to be holistic during decision making, rather than a lack of knowledge of what ESs are affected by weir modification being a barrier to the implementation of a holistic approach.

The ES typology identified in this chapter is not completely ready for use in evaluating weir modification options. There are other criteria that fall outside the definition of ESs that are important to consider in decision making; obvious ones being the resource costs of weir modification e.g. money, materials, and the disturbance that weir modification might cause to human activity on the river bank. Also it is quite possible that significant ESs exist that have not been identified in this chapter. Humans are still developing a full picture of the benefits ecosystems provide, and new ESs might still remain be to be discovered (Ceballos & Ehrlich 2009).

The actual implementation of the typology as a framework to assess alternative weir modification scenarios poses a major challenge. One of the most difficult types of ES to consider in decision making are sociocultural values. As has already been discussed, a vast number of sociocultural values can be potentially affected by weir modification. These values do not have to be held by local stakeholders, and do not respect catchment or administrative boundaries e.g. many people in the UK care about the welfare of animals in other countries such as tigers, whales and pandas that they never expect to meet. Ideally the sociocultural values of the entire global human population should form part of an evaluatory ES framework, though the decision maker must instead find a practical and equitable method to select a representative subset of values.

Sociocultural, aesthetic and recreational ESs are problematic for another reason. They often consist of abstract or subjective notions such as biodiversity, naturalness, fun, or other conceptions that stakeholders may find hard to explain and define. Predicting how a management intervention will then affect these values is difficult because of the qualitative and uncertain nature of some of the predictive variables (Schaich *et al.* 2010). As such it can be difficult to apply conventional modelling approaches to predict these ESs. This is probably why sociocultural values have tended to be neglected in the ES literature (Schaich *et al.* 2010, Daniel *et al.* 2012). For example, Rey Benayas *et al.* (2009) found 524 quantitative indicators for various ES types, but none explicitly considered sociocultural ES provision. The consequence is that ES accounting is biased against sociocultural ESs (Schaich *et al.* 2010). The identification of appropriate modelling approaches that can deal with the difficulties of modelling sociocultural ESs should be a research priority and is necessary if the ES paradigm is to fully deliver the expected holistic benefits.

Another major modelling challenge is the interdependent effects multiple weirs can have on the provision of most of the ESs (see Table 2.2). Not only do weirs need to be considered on a case by case basis so that their own unique environmental, sociocultural and economic context can be accounted for, but a strategic catchment wide overview must be maintained so that interactions between weirs can be factored into decision making. Modelling approaches must therefore be developed to provide decision makers with the capacity to understand how the interventions they are planning will interact.

Once the ESs can be predicted, an option is to assign monetary values on the magnitude of provision. This is increasingly done, though the issue of whether or not to monetise ESs is controversial (Gómez-Baggethun *et al.* 2010). One advantage of the monetary approach is that it allows summation of ecosystem services, so that cost benefit analysis can be conducted. This can be particularly effective in persuading institutions that are economically orientated (e.g. corporations, governments) to make interventions or change management practices if it can be shown that this will result in more savings or profits. The monetisation of ESs is also thought to result in decision makers taking them more seriously (Chee 2004).

But putting monetary values on ESs is sometimes seen as unnecessary or unhelpful (Gowan, Stephenson, & Shabman 2006; Defra 2007a). Methods to assign financial values to ESs have significant limitations. Market values are sometimes used (e.g. the price of fish to calculate the entire value of a fish stock) but these do not necessarily capture the importance of an ES in terms of the welfare it provides. A fish stock could be a vital source of protein to an impoverished population, but its market value may be small due to the lack of money held by this stakeholder group. In contrast, consider the welfare benefits that arise from a luxury car. Classical economics also fails to value natural capital well because processes that provide wealth in the short term usually have more value placed on them than those which accrue benefits over a longer timespan (Chee 2004). In addition, techniques that capture value by conducting surveys enquiring what people are willing to pay for the provision of an ES assume that humans are rational actors with a perfect knowledge of the economy, assumptions that are far from true (Chee 2004).

In the context of weir modification decision making it is suggested that it is not helpful to monetise the evaluatory framework of ESs. Not only are the values of dubious accuracy, but stakeholders are likely to find the information of how much their values are worth alienating, rather than useful. Also, many ESs such as the sociocultural ESs are not considered to have an absolute value, rather it is a matter of perception, which usually varies from one stakeholder group to another. Instead information to allow the decision maker to judge the relative importance of different ESs should be provided.

The last remaining step in the implementation of the ES framework to assess weir modification regards the question of how it should be employed by the decision maker. Because, as was referred to in chapter 1, the human mind is only able to receive, process and remember a limited amount of data (Miller 1956), and because of the large number of ESs that will compose an evaluatory framework, it is suggested that it best be applied using a decision support system (DSS), in which all the ES models can be integrated and interacted with through a user friendly graphical interface in a more manageable way. Such a DSS will need to inform the user how the provision of the framework of ESs is affected by weir modification by using models of the ESs. This chapter has raised the issue of the difficulty of modelling sociocultural ESs, which are important in the Don Catchment, so in the next chapter the question of how this can be done is investigated.

3 The use of Bayesian Networks to model sociocultural ecosystem services: A Canoeing Case Study

3.1 Introduction

Much of the value of a river is a product of the way it can enrich our lives through the recreational and aesthetic experiences it provides us, and because we get satisfaction from the existence of it and its elements or processes, for their own sake (Krutilla 1967). The general global trend of provision of these sociocultural ecosystem services (as they are collectively termed in this chapter) is of decline, because humans have often traded them off against other interests such as agricultural production (Millennium Ecosystem Assessment 2005). Predicting how river interventions affect these sociocultural ecosystem services (ESs) is necessary if the holistic principle of ICM is to be applied to catchment management and they are to be considered in the decision making process (Ticehurst *et al.* 2007). However, producing models with the necessary predictive capabilities to do this is far from easy, due to the qualitative nature of many of the variables that compose sociocultural ES. This may explain the fact that Rey Benayas *et al.* (2009) found many examples of other types of ES being used as evaluatory criteria with which to assess ecological restoration projects but no examples of sociocultural ESs. In addition, water management policy has traditionally focussed on physical objectives such as chemical water quality, so there has been a lack of impetus to consider sociocultural ESs in the decision making process (Woods 2006). This situation is currently changing, with the introduction of the Water Framework Directive (WFD) in the European Union, which provides some scope for sociocultural ESs to be traded-off against other objectives (Hanley & Black 2006). The capture of human perceptions and values in models is now considered a key research direction in the development of tools to aid water management (Borowski & Hare 2007). Yet if this integration of sociocultural ESs is to be achieved then the problems that come with it – complexity, uncertainty, and subjectivity of the relationships between variables – must be overcome.

One solution is to take the modelling approach of a Bayesian Network (BN). In the last decade BNs have increasingly been applied to environmental management problems, and recently also to integrated water management issues (Ames *et al.* 2005; Barton *et al.* 2008; Kumar *et al.* 2008). BNs use a graphical cause-effect network that utilises probabilities to describe the conditional relationships between the dependent variables (known as child nodes) and independent predictive variables (parent nodes) (see Figure 3.1). Each of these variables is described as a range of discrete states (e.g. group of organism could be vertebrate, invertebrate, plant, or other). If a variable is continuous (e.g. organism size), then this must be split into distinctly defined ranges (e.g. high, >100kg; medium,100-1kg; low, <1kg).

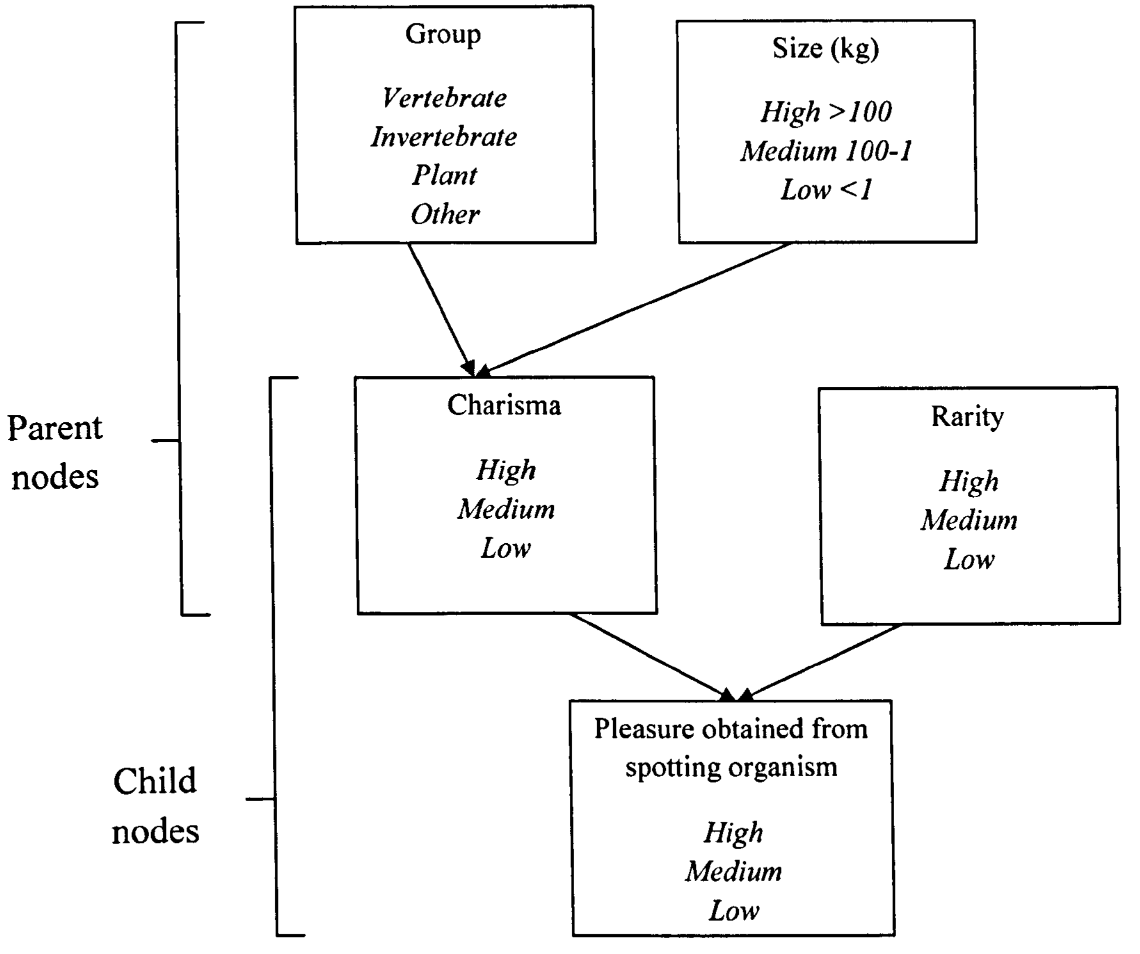


Figure 3.1. An acyclic graph of a hypothetical BN that predicts the likelihood that an individual will take pleasure in spotting an organism, based on the predictive variables size, category of organism, and rarity of organism. The states of each node are italicised.

The user of the BN does so by specifying the state of parent nodes, which the BN uses to calculate the likelihood of each child node state resulting. Child nodes may also be parent nodes of further child nodes creating a chain through which the probabilities propagate until a basal child node is reached. For example, in the hypothetical BN displayed in figure 3.1 that predicts the likelihood that an individual will take pleasure in spotting an organism, the user might specify that the organism in question is a vertebrate, its of a medium size, and it is rare. The basal child node will then output instantaneously that the likelihood that the individual who spotted the organism will have a high amount of pleasure is 70%, medium is 20%, and low 10%. By using probabilities, relationships between variables can be derived from expert judgement, and uncertainties in expert knowledge can be captured (van Kouwen, Schot, & Wassen 2008).

These qualities make a BN approach suitable for modelling the relationships between weir modification and sociocultural ESs. The graphical user interface (GUI) of a cause-effect network means the model is relatively transparent ('white box' as opposed to 'black box'), with the model variables and the relationships between them clear to see. By describing relationships between variables probabilistically, mentally held perceptions and judgements of value can be described, allowing the views of stakeholders to be harnessed. Probabilities can capture differences in opinion between stakeholders which are then represented as uncertainty in the model. This is important when dealing with the inherently variable nature of subjective variables, where potentially every individual can hold a unique view.

In this paper the principle of using a BN to model a sociocultural value is tested by constructing one to predict a sociocultural ES provided by the rivers in the Don Catchment, that of the impact of weirs and weir modification on the quality of the rivers for canoeing. The experiences of building the BN collaboratively with canoeing groups is discussed and issues regarding the utility of the approach for modelling sociocultural ESs explored. What did and did not work well in the process of building the model is examined and the suitability of BNs for modelling sociocultural ESs is commented on.

3.2 Canoeing and weir modification in the Don Catchment

Canoeing is a popular recreational activity in the Don Catchment, with multiple canoeing groups using the Rivers Don, Dearne and Rother. An interview was held with Sheffield Canoe Club in the autumn of 2008 which confirmed that weirs and weir modification are of interest to canoeists and can affect the recreational quality of the rivers for canoeing. A stretch of the Don in Sheffield is known to the canoeists as 'the five weirs paddle'. The interview revealed that weirs can both increase or decrease river quality; they make rivers more dangerous therefore reducing quality, but they can also make rivers more fun, increasing quality. Certain weir modifications can affect fun and danger. The installation of a canoe pass for instance increases the safety of a weir.

Whether a weir is dangerous or fun or not is subjective; based on the personal judgement of individual canoeists. Weir danger and weir fun is dependent on an interplay of qualitative variables that are hard to define, especially in a mechanistic sense. Furthermore, each weir is unique, and so it is not possible to generalise the effect of weirs based on a generic type. For these reasons, mechanistic or rule-based models are inappropriate methods for predicting how weirs and weir modification determine river quality. However, the relationship between subjective variables can be described probabilistically. This made a BN suitable for modelling how weirs affect river quality for canoeing.

3.2 The construction of the canoeing BN

In the following sections the four steps in the process of constructing the BN built to predict the impact of weir modification on the recreational quality of rivers are described. This process of deriving expert judgement to construct the model is known as 'knowledge elicitation'.

3.2.1 Identification of model variables and structure

The first step of building an expert built BN is for the experts to identify the variables and the structure of the cause-effect network. Two workshops with local canoe groups were held to achieve this step. Six local canoeing groups were identified using the internet or through contacts and invited to attend. Of these, three agreed to send representatives providing a total of five participants who were divided into two groups attending separate workshops. It is not clear why three groups did not participate, but these groups were only contactable by email, and it might reflect the impersonality and frequency of junk mail associated with this communication medium. The number of experts involved in BN construction was relatively low, and the fewer experts involved in the construction of a BN, the less the likelihood that the resultant BN will reflect the opinions of the wider expert community. However, BNs are frequently built with as few as three experts as construction is very demanding of the participants in terms of time and effort (Kumar pers. comm.). Therefore the number of canoeists involved during construction is acceptable.

After explaining the objectives of the workshops, the process of creating the structure of the BN started with an informal group brainstorming exercise. The canoeists were encouraged to think about how a weir could affect the quality of a river for canoeing; a variable that was the basal child node in the network. As was described when the canoeists were first interviewed, the canoeists explained that a weir could affect quality in two ways; as a source of danger, and as a source of fun (descending weirs is considered exciting). These variables therefore became parent nodes to the basal child node. The process was repeated, this time by thinking about what factors determined the danger and fun of the weir. The danger of a weir for example is determined by two factors; what the canoeists term drawback, which is a hydraulic roller at the foot of a weir that pulls the canoeist against the flow of the river into the water cascading over the weir face (see Figure 3.2), and the risk of obtaining injury from an impact with the weir structure or the debris on the river bed. This process of determining factors was continued until measurable quantitative variables were identified that could form the input nodes to the structure of the BN.

The next step was to factor in the impact of weir modification options (changing weir height, steepness, orientation, profile of weir face, and installation of microhydro, canoe pass and fish passes). These were described to the canoeists who then discussed whether they had any influence over any of the model variables, and were included if they did. Lastly, the importance of each node was discussed and excluded if it was thought that one would not make much difference to the output of its child nodes (see Figure 3.2 for an overview of the evolution of the network). This stage of BN construction is reliant on the experts to identify all significant variables and their causal relationships. As the process of identifying the structure of the model and its variables was done in a collaborative manner, there is a risk that the opinions of more outspoken or domineering individuals would be overrepresented in the results of the workshop (Tayie 2005). This is a limitation with obtaining information in a workshop setting. To reduce this risk, effort was made to involve all individuals in the discussions by prompting input from all participants. It was not apparent that any individual opinions dominated the process. Despite the risks associated with obtaining information in a collaborative fashion, a recognised advantage is that the sharing of information between experts can be important in building consensus and stimulating thought (Tayie 2005). Because two workshops were held, two

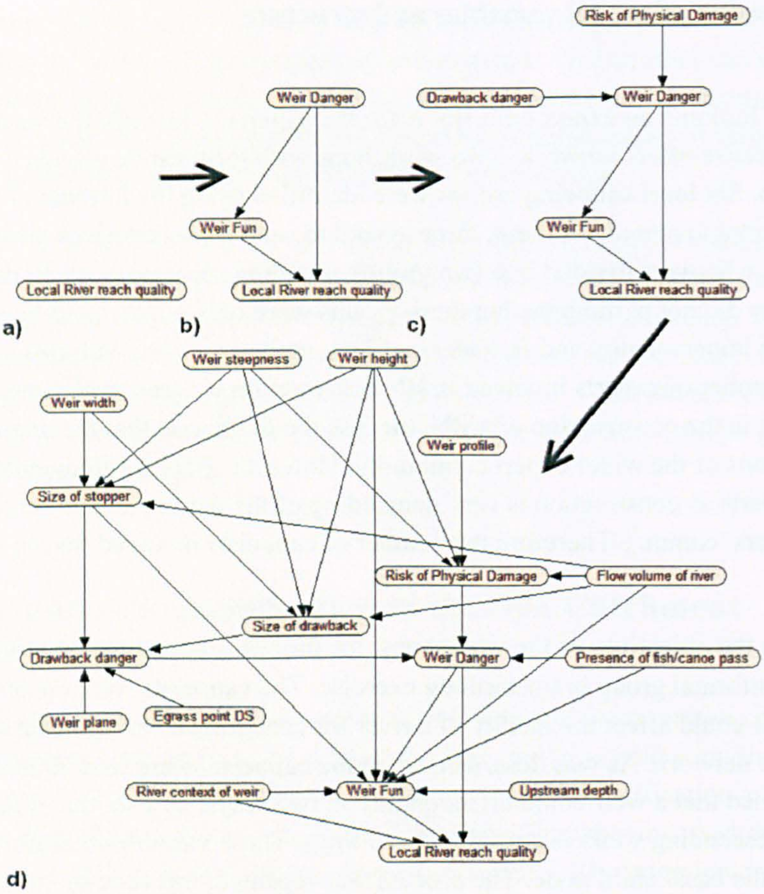


Figure 3.2. The evolution of the BN structure in the identification of model variables and structure stage. a) The basal child node of river quality, b) Weir fun and weir danger were identified as the two main ways weirs impact on river quality for canoeing, c) Weir danger was found to be controlled by the weir drawback (cyclical river flow at the base of the weir) and risk of physical injury descending the weir, d) The final canoeing BN structure with all remaining parent nodes and linkages identified.

separate model structures were developed independently. As the same variables and relationships emerged during the workshops and the resulting mode structures were consistent, then this signifies that they are likely representative of the opinions of the wider canoeing community. It cannot however be assumed that the opinions of the canoeing community are necessarily correct.

3.2.2 Categorisation of the variables

One characteristic of BNs is that model variables are dealt with as discrete states e.g. weir height can be described as high, medium and low. This means that the experts must be relied on to define the variables so they mean the same thing to all involved in the use and construction of the model, and also that the threshold between states is at a point that results in a meaningful change in the predicted state of the dependent variable. For instance, changing weir height from

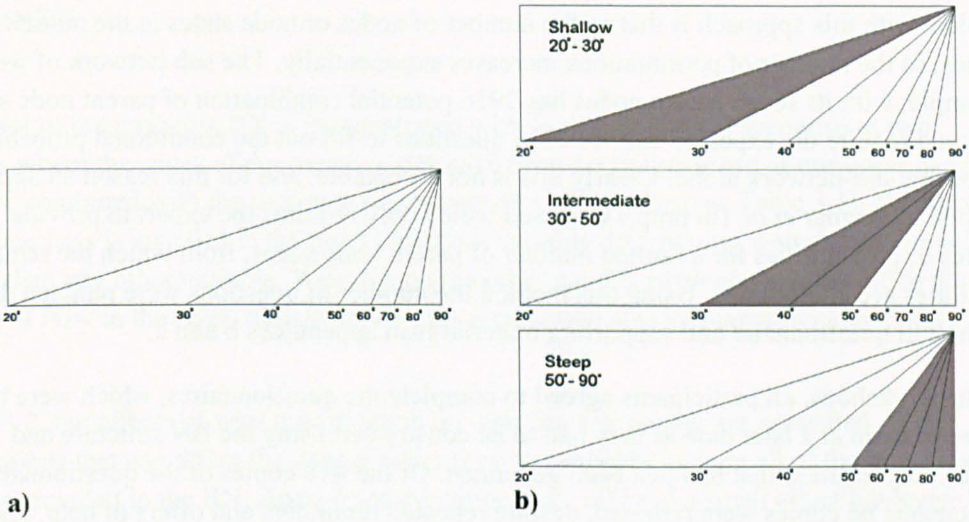


Figure 3.3. a) Visual aid used to help the canoeists classify the states for the variable weir steepness. b) The resulting ranges of weir steepness allocated to the discrete states of shallow, intermediate and steep.

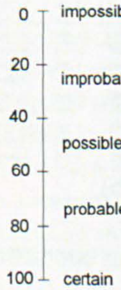
2m to 3m tall makes a pronounced difference to the risk a canoeist faces descending a weir, but a change in height of 10m to 11m makes little difference. This process was also conducted at the same workshops, and again there was a minor risk of biases due to collaboration, though this was a necessary risk. The step was aided using prepared visual aids for those variables anticipated likely to be important to the canoeists (e.g. see Figure 3.3.).

3.2.3 Probability elicitation

This stage requires the completion of conditional probability tables for each relationship between a child and its parent nodes, where the experts are relied upon to estimates the likelihood of child node being in each of its states for every permutation of parent node states (see Figure 3.4). An example question for one permutation:

If the danger of a weir is low, weir fun is high, and river context is an upland river, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)



	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

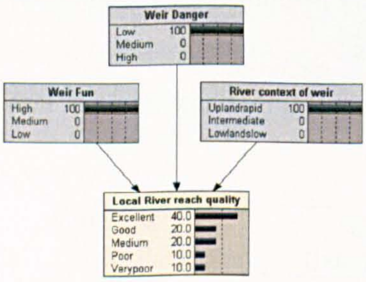
! Estimates should add up to 100!

Comments:

A problem with this approach is that as the number of nodes or node states in the model increases, so the number of permutations increases exponentially. The sub-network of weir fun for example, with its seven parent nodes has 2916 potential combination of parent node states. This would require the expert to answer 2916 questions to fill out the conditional probability table for this sub-network alone! Clearly this is not acceptable, and for this reason an approach developed by Kumar *et al*. (in prep.) was used which only requires the expert to provide estimates of probabilities for a limited number of parent node states, from which the remaining probabilities are interpolated. Using this method the number of questions were reduced down to 120. The full questionnaire and supporting material is in appendices b and c.

After the workshops, all participants agreed to complete the questionnaires, which were to be provided to them at a later date as they had to be constructed using the BN structure and variable categorisation that had just been generated. Of the five copies of the questionnaire sent to participants no copies were returned, despite repeated reminders and offers of help. As this first attempt at probability elicitation failed, a change in tactic was tried. Supposing that that the lack of success was due to the length of the questionnaire and its asocial nature as compared to the workshops, new canoeing contacts were made and were personally supervised when filling out the questionnaires. The process of completing the questionnaires was very time consuming, taking between 2 to 5 hrs. Participants needed to spend time thinking about the questions and often referred to the supervising helper for further explanation, and to check that they had interpreted the questions correctly. It is perhaps fortuitous that a supervisory route was taken, as it is doubtful whether the questionnaires would otherwise be fully understood. Because the process was so time consuming and required much mental effort from the participants, one risk is that they became increasingly mentally fatigued and bored the more questions they answered, and so error in their estimates may have risen due to declining concentration or haste to finish.

Following probability elicitation, the probabilities were fed into the commercially available BN modelling software Netica, which displays the causal structure of the BN in its GUI, with which the user can interact and receive feedback in real time.



a)

Weir Danger	Weir Fun	River context of weir	Excellent	Good	Medium	Poor	Verypoor
Low	High	Uplandrapid	40.000	20.000	20.000	10.000	10.000
Low	High	Intermediate	27.200	20.000	32.800	10.000	10.000
Low	High	Lowlandslow	27.200	13.600	16.800	13.200	29.200
Low	Medium	Uplandrapid	28.800	20.000	31.200	10.000	10.000
Low	Medium	Intermediate	16.000	20.000	44.000	10.000	10.000
Low	Medium	Lowlandslow	16.000	13.600	28.000	13.200	29.200
Low	Low	Uplandrapid	28.800	14.400	17.200	12.800	26.800
Low	Low	Intermediate	16.000	14.400	30.000	12.800	26.800
Low	Low	Lowlandslow	16.000	8.000	14.000	16.000	46.000
Medium	High	Uplandrapid	24.000	20.000	36.000	10.000	10.000
Medium	High	Intermediate	11.200	20.000	48.800	10.000	10.000
Medium	High	Lowlandslow	11.200	13.600	32.800	13.200	29.200
Medium	Medium	Uplandrapid	12.800	20.000	47.200	10.000	10.000
Medium	Medium	Intermediate	0.000	20.000	60.000	10.000	10.000
Medium	Medium	Lowlandslow	0.000	13.600	44.000	13.200	29.200
Medium	Low	Uplandrapid	12.800	14.400	33.200	12.800	26.800
Medium	Low	Intermediate	0.000	14.400	46.000	12.800	26.800
Medium	Low	Lowlandslow	0.000	8.000	30.000	16.000	46.000
High	High	Uplandrapid	24.000	12.000	16.000	14.000	34.000
High	High	Intermediate	11.200	12.000	28.800	14.000	34.000
High	High	Lowlandslow	11.200	5.600	12.800	17.200	53.200
High	Medium	Uplandrapid	12.800	12.000	27.200	14.000	34.000
High	Medium	Intermediate	0.000	12.000	40.000	14.000	34.000
High	Medium	Lowlandslow	0.000	5.600	24.000	17.200	53.200
High	Low	Uplandrapid	12.800	6.400	13.200	16.800	50.800
High	Low	Intermediate	0.000	6.400	26.000	16.800	50.800
High	Low	Lowlandslow	0.000	0.000	10.000	20.000	70.000

b)

Figure 3.4. a) Subnetwork of the canoeing BN and b) corresponding conditional probability table.

3.3 Results

The output of the canoeing BN is demonstrated with four hypothetical scenarios at two extremes where the states of the parent nodes have been set to maximise or minimise danger. These are combined with the presence or absence of a canoe pass (see Table 3.1). Whether or not a canoe pass is installed is the most important variable determining weir danger, greatly more so than any other variable. Weir fun on the other hand is particularly sensitive to the quantity of flow in the river, though canoe pass installation also increases fun a moderate amount.

In table 3.2, the effects of weir modification on weir fun and danger are presented. Weir modifications that can affect the danger weirs pose to canoeists include all of the modification variables included in the BN. Apart from the canoe pass, all have a small effect however. Weir fun on the other hand is only affected by canoe pass installation and weir height.

In terms of utilising canoeists to construct the BN, some but not all parts of the process worked well. The assembly of BN structure progressed quickly and without incident. Workshop participants found the cause-effect network intuitive, and seemed very engaged; enjoying talking about canoeing. The same applies to the categorisation of the variable states. However in contrast to the previous steps, the process of eliciting the probabilities caused problems for the model construction, with canoeists needing careful supervision to fill out the probability questionnaires.

3.4 Discussion and conclusion

By creating a BN to model the impact of weir modification on the quality of the River Don for canoeing, it has been demonstrated that this technique can be used to model sociocultural ESs. With a working model and clear path to validation and improvement planned out, it is expected that the predictive ability of the final version of the BN will be fairly accurate. By using

Table 3.1. The output of the canoeing BN for two scenarios with and without canoe passes installed.

		Probability (%) that weir danger is:			Probability (%) that weir fun is:		
Scenario described as BN parent node states	Canoe pass	High	Medium	Low	High	Medium	Low
The river is upland, rapid and has a high flow.	No	92.8	4	3.2	34.4	33.7%	31.9
The weir is high, narrow, has a rough profile, of an intermediate steepness and a perpendicular plane.	Yes	29.6	51.6	18.8	38.9	38.4%	22.7
The river is lowland, slow and has a low flow.	No	54.2	40.8	5	6.4	5.3%	88.3
The weir is low, wide, has a smooth profile, of a low steepness and a 'smiling' plane.	Yes	1.2	4	94.8	11.5	13.8%	74.7

Table 3.2. The effect of weir modifications on weir danger and fun. The effect of each modification was tested while the other predictive variables had their probabilities balanced across all of their potential states (e.g. 33% high, 33% medium, 33% low).

Change to weir	Weir danger	Weir fun
Canoe pass installation	+ve (less dangerous)	+ve
Increasing weir profile roughness	-ve	Trivial (<1% change)
Increasing weir height	-ve	+ve
Increasing weir steepness	-ve	Trivial (<1% change)
Change weir plane to 'smiling'	+ve	Trivial (<1% change)
Change weir plane to perpendicular	-ve	Trivial (<1% change)

conditional probabilities to describe the relationships between variables, the canoeists were able to successfully express how model variables affected subjective concepts such as 'weir danger' or 'weir fun'. In addition, the canoeists were comfortable using probabilities to convey the inherent uncertainty in the relationships between these qualitative variables.

The BN indicates that the characteristics of a weir can have a large effect on how much danger a weir poses or how much fun it is to chute. It also suggests that weir modification, either canoe passes built specifically for canoeists, or modifications implemented for other reasons, affect weir danger and fun. The scenarios where BN node states were selected to either minimise or maximise danger show that canoeists perceive the installation of canoe passes as being highly effective in reducing the danger of a weir. The likelihood of a weir having a high level of danger is reduced by over 50% by the installation of a canoe pass both when danger is maximised or minimised. Interestingly, it also appears that weir fun and weir danger are correlated, though perhaps this is not surprising since danger is one factor that can determine how exciting an activity is.

The installation of a canoe pass was the only type of weir modification that had a substantial effect on the danger posed by a weir (the impact of others being much smaller). It is possible that this result is an artefact of the structure of the BN, which other studies have found can result in the under prediction of effectiveness of management interventions (Varis & Lahtela 2002; Ames *et al.* 2005). Uncertainty can propagate through chains of nodes in a BN, so that it is magnified when the probabilities are passed from parent to child (Barton *et al.* 2008). The problem is exacerbated due to the discretisation of continuous variables. The fewer states a node has, the smaller the amount of information that can be passed down the chain, thereby increasing uncertainty (Ames *et al.* 2005). As a result, during probability elicitation stage, model builders are faced with a trade-off between less uncertainty in the BN and fewer questions in the questionnaire. As the canoe pass node is a direct parent variable of the weir danger node, while the other types of weir modification are linked to danger through intermediate nodes, the implication is that the predicted importance of the canoe pass is a consequence of this structure rather than a reflection of its actual significance.

Based on the author's observations the predictions of the BN generally concur with how the canoeists in the workshop described what factors determined whether weirs are fun or dangerous. However, there are multiple relatively minor inconsistencies. In the workshops, the canoeists agreed that the most dangerous weir plane was one that was 'frowning' (see Figure

3.1.), while the BN calculates perpendicular weirs as the most dangerous. Also, the canoeists stated that some weirs are not dangerous but the BN predicts that the safest weir without a canoe pass had a 54% chance of being highly dangerous. While the canoeists who filled in the questionnaires were different to those at the workshop, this does not seem likely to have caused these apparent contradictions, as they also voiced the similar opinions on weir plane and weir danger. Therefore the model does contain some minor discrepancies.

It was not feasible to validate the BN during the course of this study. To do so would have required the comparison of the models output to data collected on the fun and danger of weirs. Canoeists would need to chute weirs for which the dimensions are known, and for each descended, the canoeists would have rated its characteristics e.g. weir fun and danger. These could then be compared to the weir fun and danger states predicted by the BN used a Chi-squared type statistic. This process would provide a robust assessment of the validity of the expert knowledge captured in the BN. Validating the causal networks of BNs is more problematic (Barton *et al.* 2008), but if the predictions of the model are found to be correct then this is less of a problem. Attempts to arrange the validation of the model were made during the course of this research, though cancellations by the canoeists meant that it was not possible. This is not an issue as despite the minor discrepancies, the model is generally consistent with what the canoeists described during the interview stage. Ultimately the objective of this chapter is to test using a real case study the capacity of BNs to predict sociocultural ESs, which was successfully achieved. Any inaccuracy in the BN would not undermine the validity of the decision making experiment in chapter 6 as while the experimental group used the BN, the control group used a basic set of rules that were constructed using the results of the BN. Therefore there was consistency in the information that was provided to the two groups regarding how weir modification affected weir danger and fun for canoeists.

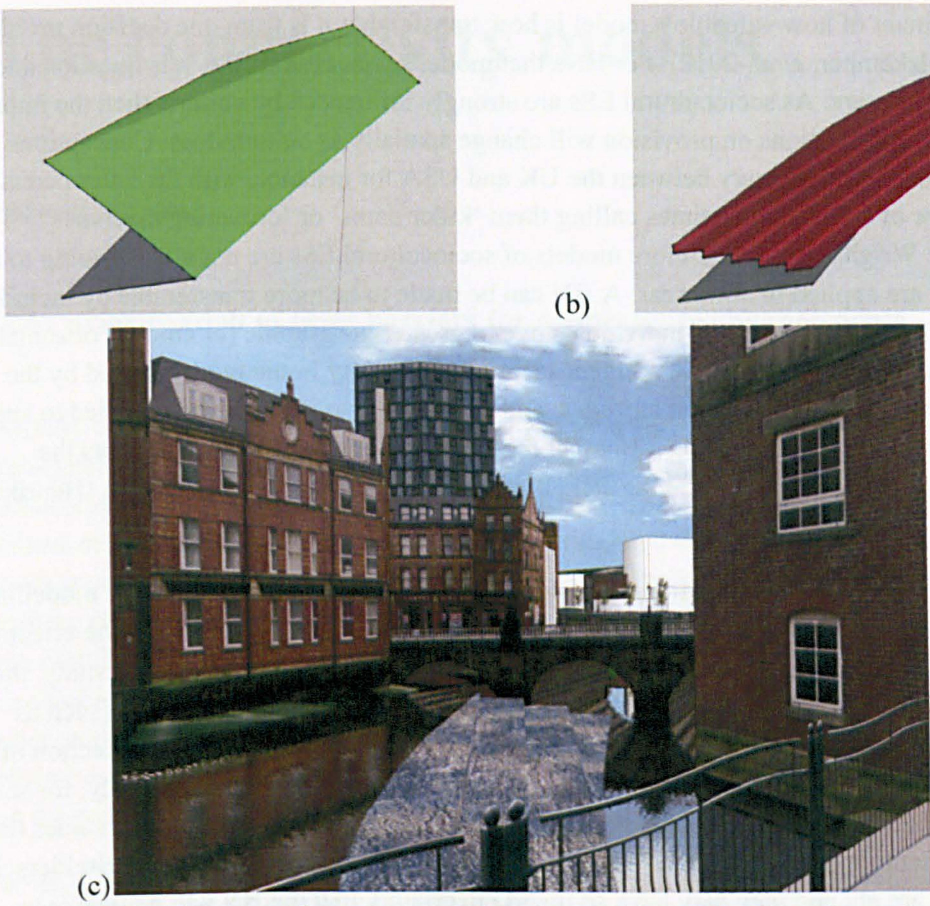
In hindsight the step of model validation could likely be improved by incorporating it into the process of model construction. Indeed, it is suggested that instead of a process of requiring experts to fill in a single, rigidly structured questionnaire that is then fed into the model at a later date in the absence of the experts, a more flexible iterative process is desirable. It would be more efficient if probabilities were elicited for each model subsection, and these were used to train this subsection with supervision from the experts. In this way the experts could check the probabilities they provide, and so validate that the BN represents their perceptions in a piecemeal fashion. However, this will be even more time consuming, and so it may be difficult to find stakeholders willing to provide this kind of commitment.

The process of constructing a model using expert knowledge must be relatively user friendly, and in this regard the BN could generally be said to be successful. The canoeists found the steps of identifying the variables and structure of the model, and categorising the variables engaging and relatively intuitive processes. However as in the experience of Henriksen *et al.* (2007), who found aspects of BNs difficult for non-experts to understand, the canoeists also struggled with one part of BN creation. In our case, this was the probability elicitation stage, required to create the conditional probability tables. While it is not known why none of the first set of questionnaires distributed were returned, it seems reasonable to assume that it was due to the length and the abstract nature of the questionnaire. Trying to envisage the multiple states of a set of parent nodes described in text is difficult, and indeed those supervised to fill out the questionnaire found it challenging. The large number of questions required in the probability elicitation stage, an outcome of dependence on expert knowledge, was also demanding of the stakeholders. As the number of variables in a BN increases linearly, the number of questions needed to fill out the conditional probability tables increases exponentially. Consequently the canoeing BN would not have been practical to build without the method of Kumar *et al.* (in prep.) to interpolate probabilities from a limited number of questions. Even so the number of questions required was still large, and posed a barrier to completing the knowledge elicitation stage. For some BNs the relationships between physical variables can be described using empirical data or data from other pre-existing models, but neither were available for any of the variable linkages in the canoeing BN. In hindsight more effort should have been taken to simplify the model by removing less important variables, though this is difficult during the simplification stage as it is not always clear which of the variables can be removed without eroding the predictive ability of a BN. Ultimately the excessive demands put on experts by the questionnaires will constrain the potential complexity of BNs requiring expert knowledge. Methods need to be developed to increase the ease of completing the probability elicitation process to reduce the burden on those providing expert knowledge. The probability stage could be avoided altogether if enough feedback from canoeists on the fun and danger of weirs could be gathered so that this could be used to directly train the BN, though it is difficult to imagine how this could be conveniently achieved.

Post-construction BNs are relatively user friendly, important if stakeholders are to be involved in the decision making process. With a graphical user interface (GUI) displaying an interactive cause-effect network, BNs are an intuitive way to explore how weir modification options affect river quality for canoeists, and this transparency can help build trust. This advantage is compounded by the relative ease of constructing BNs using stakeholder participation (Henriksen *et al.* 2007).

By displaying the likelihood weir modification will result in certain variable states, the inherent uncertainty in the model is communicated to the user, though it is important to note that BNs do not differentiate between uncertainty in the system and in stakeholder understanding (Barton *et al.* 2008). As the BN structure and variables are defined by stakeholders, then it is automatically constructed at a level relevant to the stakeholders. For example, in the hypothetical BN presented in figure 3.1, stakeholder categorisation of the 'Group of organism' variable will be more appropriate than a scientific one.

This user friendliness makes it an inclusive tool, meaning BNs can be used to promote understanding between various stakeholder groups, as well as providing information to support decision making. Even so, there is still some scope for the improvement of the GUI. Consider the canoeing BN with its ten input variables describing various river and weir attributes; mentally visualising these ten variables together is difficult. Given that water managers do not have time to learn or teach the public how to use complex models (Borowski & Hare 2007), then the need for model users to mentally visualise the system is probably a barrier to BN uptake. To improve the user friendliness of the GUI is one reason why Gill *et al.* (2010) have linked the canoeing BN introduced in this chapter to interactive visualisation software. The visualisation communicates what a weir would look like based on the input states the user has selected. It allows the user to interact with the weir e.g. changing height, designing different weir modification scenarios, providing an intuitive way for stakeholders to participate in decision making (e.g. see Figure 3.5).



(a) (b) (c)

Figure 3.5. 3D visualisations of a weir coupled to the canoeing BN. The weir can be manipulated by the user by changing its height etc, and receive feedback from the BN on how likely the new form will be fun or dangerous. a) The BN predicts that this weir will be safe so it is coloured green. b) This weir is predicted to be dangerous so it is coloured red. c) The BN can be coupled to a realistic 3d visualisation to give an idea of context. The pictured weir is Lady's Bridge Weir in the centre of Sheffield.
Source: Adapted from Gill *et al.* (2010)

However, BNs also have some disadvantages in addition to the problems discussed earlier that limit their usefulness for modelling sociocultural ESs. BNs cannot easily deal with spatial information (Holzkämper, *et al.* 2012), meaning that while the canoeing BN can predict how individual weirs are affected by weir modification, it cannot consider the cumulative effect of multiple weirs on stretches of river. Other approaches must be used in conjunction with BNs if spatial issues are to be dealt with. BNs may also be limited as tools for decision makers. Borowski *et al.* (2007) found there was a need for models that helped the user to develop new solutions to management problems. As discrete management options are predefined in the BN, then scope for users to design new management options is restricted. This limitation can be partially overcome by allowing and encouraging users to modify the BN, incorporating new ideas after its initial construction. But if stakeholders do not know what the effects of a new modification variable will be, then it cannot be included until this understanding is gained. A further issue is that the categorisation of the variables into discrete states makes the BN unresponsive to small changes in input variables, meaning the tool is not useful for fine tuning designs.

One determinant of how valuable a model is how transferable it is from one decision problem to another (Holzkämper, *et al.* 2012). For BNs that model sociocultural ESs, it is questionable how transferable they are. As sociocultural ESs are strongly influenced by culture, then the impact of management interventions on provision will change spatially as culture does. Conceptions of how dangerous weirs are vary between the UK and USA for instance, with the latter perceiving them as more of a threat, sometimes calling them 'killer dams' or 'drowning machines' (Tschsntz & Wright 2011). Therefore models of sociocultural ESs are not always going to be valid if they are applied in new areas. A BN can be made to be more transferable by including in its construction a wider range of individuals over a greater geographic (or cultural or social) range. This comes with the cost of a higher level of uncertainty in the model caused by the incorporation of a greater range of attitudes, and as a result less precise when applied to specific problems. In addition, transferring a BN that models a sociocultural ES circumvents the advantage of the approach of allowing stakeholder participation in its construction (Henriksen *et al.* 2007).

Lastly, some questions still remain on the applicability of the BN approach for the modelling of sociocultural ESs. While the relationships and variables involved in determining the effect of weir modification on the quality of a river for canoeing were clear cut in this case study, this may not be the situation for other sociocultural ESs. Indeed, some cultural values (such as perceptions of spiritual or aesthetic value) may resist being reduced down to a collection of variables, because stakeholders are either unwilling or unable to do so. Additionally, for some sociocultural ESs there can be such a wide range of perceptions and judgments of values that it makes it difficult to develop a model structure that can be agreed upon by all stakeholders. If probabilities are elicited they may have so much uncertainty that the BN will be unable to provide useful predictions. In order to answer these questions, further research is required on the utility of BNs to predict sociocultural ESs.

The canoeing BN is integrated into the Weir Tool decision support system introduced into chapter 5 so that it can be used to assess weir modification options in the Don Catchment and is stored on the CD that comes with this thesis.

4 The connectivity models

4.1 Introduction

4.1.1 The prioritisation of river barriers for connectivity enhancements

Connectivity is very important in determining the physical and ecological attributes of a river. The significance of the continuous connected structure of rivers is recognised by the River Continuum Concept (RCC), which describes fluvial systems as being in a state of dynamic equilibrium driven by the unidirectional flow of water down a catchment (Vannote *et al.* 1980). The result is continuous gradients of physical variables beginning at a river's headwaters and ending at its estuary. As a general rule, most rivers start as relatively high gradient erosive streams, deriving the majority of their energy input from allochthonous sources, transitioning into rivers of intermediate size and gradient in which autochthonous productivity is most important, and end as larger slower meandering sediment laden lowland rivers where allochthonous energy inputs is again most important. The RCC uses these physical gradients to explain the patterns in the composition of ecological communities found in river systems.

Yet the RCC describes natural rivers, whereas in reality many are heavily impacted by human activity. In particular, manmade river infrastructure such as weirs and dams interrupt the longitudinal continua of physical attributes. For example, impoundments reduce gradients, increase depths, and cause rivers to deposit sediment, with the converse conditions occurring downstream (Baxter 1997). When rivers have multiple impoundments (as they often do), an alternating series of lotic and lentic habitats and corresponding ecological communities is created, termed the Serial Discontinuity Concept (Ward and Stanford 1983).

As well as interrupting physical gradients, manmade infrastructure also pose barriers to the movement of aquatic organisms through river systems. They thereby change the spatial structure of river networks, fragmenting them into isolated sections of habitat. This is significant as the spatial structure of an ecosystem is important in determining population dynamics and persistence (Dunning, Danielson, and Pulliam 1992) and species distributions (With, Gardner, and Turner 1997). Because the structure of river networks is continuous, hierarchical and dendritic, it sets them apart from other ecosystems, resulting in patterns of species distribution specific to fluvial systems (Brown and Swan 2010).

The negative impact of river barriers on fish dispersal has been well documented (Lucas & Frear 1997; Aarestrup & Jepsen 1998; Utzinger *et al.* 1998; O'Connor *et al.* 2006), but it has also been recorded to affect macroinvertebrates (Benstead *et al.* 1999) and even plant propagules (Jansson *et al.* 2000). The outcome for some species can be profoundly negative. In extreme but not uncommon circumstances, species can be extirpated from an entire catchment if a key migration route is blocked. Where river barriers are common, as they are in many river catchments, understanding how they affect river connectivity is necessary if the distribution of fish across a catchment is to be understood (Meixler, Bain, and Walter 2009).

A major class of river restoration interventions focus on the mitigation of the negative impacts of river barriers e.g. modifying weirs by installing fish passes, dam removal, and deculverting. By returning river connectivity, such measures can result in the dramatic recovery of impacted species (Meadows 2001), and are one of the most cost effective river restoration interventions (Roni *et al.* 2002).

Many of the species that benefit most from the restoration of river connectivity are commercially, culturally or socially valuable, and so in many countries there is a considerable willingness to invest substantial time, money and effort into mitigating river barriers. The Environment Agency (EA) anticipate that fish passage enhancements will be one major type of measures that will be used to achieve the nation's WFD targets (Environment Agency 2009).

But even with a willingness to make large investments, numbers of river barriers far exceed the resources required to remediate them all. A single fish pass on a weir in the UK may cost up to £500,000 (Environment Agency 2011), and with over 16,500 weirs in England and Wales (Environment Agency 2010a), improving the passability of all is financially unviable (even less so when other barriers such as culverts are considered). Instead, only a small subset of barriers can be modified, which is why a variety of techniques have been developed to aid decision makers prioritise those barriers that will bring the most rewards if modified.

One of the most simple and commonly applied barrier prioritisation approaches are scoring-and-ranking systems. These award scores to all barriers in a catchment based on the benefits (e.g. proportion of catchment upstream of barrier) and costs (e.g. total costs of mitigation) associated with modification. Those barriers that have a higher ranking score are deemed a priority for modification. One such system has been developed for the EA for application to the north east region of England (including the Don Catchment), and uses the following criteria (Environment Agency 2011):

- Number of water bodies upstream of a weir failing WFD targets
- The WFD status of the water body the weir is located in
- The presence of Biodiversity Action Plan (BAP) species at a weir
- Approximate channel width at a weir
- Barrier porosity
- Restoration of connectivity based on an index
- Number of barriers upstream
- Number of barriers downstream
- The potential hydromorphological enhancement weir modification might bring
- Whether weir modification will be of benefit or detriment to recreation
- Cost of likely viable option

A major limitation with these systems is that barriers are treated independently; the existence and status of other barriers upstream and downstream of the focus barrier are at most considered superficially during the ranking process (Kemp & O'Hanley 2010) e.g. a weir may be ranked low irrespective of the habitat availability above the next weirs upstream. This leads to the recommendation of potentially inefficient modification strategies. O'Hanley & Tomberlin (2005) found that over a range of weir modification budgets, a scoring-and-ranking system was on average more than 25% less efficient than the optimal budget allocation in their case study catchment. Another drawback with scoring-and-ranking approaches is that they are not interactive; they provide static recommendations rather than allowing users to explore the consequences of different barrier modification scenarios. As barrier modifications affect multiple human interests (as discussed in chapter 1), decision makers are constrained to finding trade-offs between these rather than being able follow the recommendations of scoring-and-ranking systems. Therefore it is more useful to have flexible tools that allow decision makers to interactively explore the performances of different modification scenarios while they find a compromise between multiple human interests.

To overcome the lack of a catchment overview in scoring-and-ranking systems, Kemp & O'Hanley (2010) advocate decision making approaches that account for the dendritic structure of the river network and the hierarchical distribution and interaction between the barriers within it. Following these principles, Kuby *et al.* (2005), O'Hanley *et al.* (2005), and Zheng *et al.* (2009) have developed optimisation models that maximise the benefits of barrier mitigation by treating river systems as hierarchical tree-like structures, and by considering the interdependent effects multiple barriers have in determining access to habitat.

Such approaches are powerful in that they can be integrated with models of other human interests so that Pareto frontiers of the trade-offs between interests (e.g. length of habitat opened up versus impact on flooding) can be calculated. This information is very useful in helping stakeholders find compromises during negotiations (Soncini Sessa *et al.* 2007). For example, Kuby *et al.* (2005) demonstrated that in the Willamette Catchment, 52% of the river network could be opened up for salmon with the small loss of 1.6% of the catchment's hydropower and water storage capacity.

However, optimisation approaches share some of the same limitations as scoring-and-ranking systems in that they recommend the best solutions, rather than allow users to explore options for themselves. While optimal decisions are obviously preferable over suboptimal, decisions that are arrived at in a collaborative manner between multiple stakeholders using an interactive decision support system are more transparent and therefore more likely to be credible to stakeholders (Bromley *et al.* 2005). Furthermore, because models are abstractions of reality and are usually built by a limited number of technical experts, they often require alteration in light of new information provided by stakeholders. For example, one stakeholder might point out that a barrier is a protected heritage feature and cannot be modified, and another that a weir is falling down and likely to be washed away in the next floods; information that could affect the decision making process.

4.1.2 River connectivity in the Don Catchment

In the Don Catchment, improving the passability of weirs to enhance river connectivity for fish is a primary driver of weir modification (C Firth, pers. comm. Director of the Don Catchment River Trust), so a tool to support decision making must be able to inform the user of the consequences of different options for river connectivity. For the reasons discussed above, the scoring-and-ranking system developed for the north east of England and the optimisation models are unsuitable for incorporation into a decision support system that allows the exploration of alternative weir modification scenarios. Therefore models were developed that have the capacity to allow the interactive exploration of the effect weir modification options have on habitat accessibility for various species.

Weirs restrict the movement of multiple freshwater species in the Don Catchment. For practicality, four species were focussed on; Atlantic salmon (*Salmo salar*), European eel (*Anguilla anguilla*), signal crayfish (*Pascifastacus leniusculus*) and white-clawed crayfish (*Austropotamobius pallipes*), as these are of particular interest to decision makers. Salmon and eel are globally of high commercial and cultural value, and are conservation priorities under the UK Biodiversity Action Plan (UK Biodiversity Group. 1995). Eel has undergone such a dramatic decline in recent decades that this species is classified as critically endangered by the International Union for Conservation of Nature (IUCN 2011). Large migrations of both fish used to occur in the Don Catchment, with salmon being anadromous (moving from sea to freshwater to spawn), and eel catadromous (moving from freshwater to sea to spawn). However a combination of severe water pollution and river impoundment by weirs led to the extirpation of these species, and while water quality has improved greatly, eel and salmon can currently only access the proportion of the catchment downstream of Sprotbrough weir (Firth 1997) (see Figure 4.1). For salmon, this means it is cut off from the higher reaches of the catchment where suitable spawning grounds are widely believed to occur.

Crayfish are of interest to decision makers primarily for conservation reasons. White-clawed crayfish are a UK BAP priority species (UK Biodiversity Group. 1995) and are classed as endangered by the IUCN (IUCN 2011). Currently this species is known to exist in a small number of river reaches within upper parts of the catchment (see Figure 4.2). Signal crayfish is an invasive species introduced into the UK from North America, and is the main driver of the decline of the white-clawed crayfish. It is spreading rapidly across the UK (including within the Don Catchment), and carries crayfish plague (*Aphanomyces astaci*), a highly contagious disease lethal to white-clawed crayfish, so that whenever the two species meet, the white-clawed population is quickly eradicated (Bower 2006). In the Don Catchment, signal crayfish have spread to a variety of locations due to terrestrial vectors, but within the river network, weirs appear to hinder the spread of this species. As a result decision makers do not want to modify weirs where it would cause the range of signal crayfish to expand, especially if it would bring the two species into contact.

Figure 4.1. Location of Sprotbrough Weir in the Don Catchment. All the habitat upstream is inaccessible to diadromous fish. The weir marked downstream is actually Crimpsall Sluice that has a bypass rock ramp.

4.1.3 Chapter objectives

In this chapter, spatially explicit models are presented that have capacity to be used to explore how weir modification options affect the accessibility of habitat for the four focus species. All consider the upstream-downstream relationships of weirs so that the interaction between multiple weirs can be accounted for. They are built by using GIS to map the quantity of habitat between weirs, so the model can report to the decision maker, as a proportion of the catchment total, the relative magnitude of accessible habitat. As there is particular interest in opening up the catchment for eel and salmon, the models for these species were improved by the use of methods to discriminate between habitat quality for these species. As little information is known about the habitat requirements for eel, expert judgement was used to estimate how habitat quality varied across the catchment. In contrast more information is available on salmon which allowed a hydrological model to be used to map those flow conditions that fall within the range of what salmon have been observed to utilise. Additionally, because the efficiencies of the passage of fish at different fish pass barrier combinations are poorly understood, how varying the passability rates impacted on habitat accessibility to migratory fish is examined. The models are then used to explore different modification strategies in the Don Catchment. The advantages and limitations of the approach are discussed, and future research directions suggested.

Figure 4.2. Locations where signal and white-clawed crayfish have been recorded in the Don Catchment. Records were collated from the biological records of the local government areas that cover the Don Catchment. The river network downstream of signal records is highlighted because signal crayfish can easily spread in a downstream direction, and because the catchment is probably under-recorded (S Dangerfield pers. comm. former Sheffield Crayfish Officer) it is best to assume these areas are already colonised.

4.2 Method

4.2.1 Accounting for the interdependencies between weirs

The habitat accessibility models function by generating an indicator that represents how weir modification affects the relative quantity of habitat accessible in the Don Catchment to the four focus species. To achieve this the river network is dissected with the locations of barriers resulting in its subdivision into multiple subnetworks (see Figure 4.3) with a unique identifier (i) from 1 to n (where n equals the number of subnetworks). Barriers are of three types; weirs (how this dataset was collected is described in chapter 1), reservoirs, and several long culverts widely believed to be impassable to fish.

GIS was then used to determine the length of river within each subnetwork, providing a measure of habitat quantity (denoted as q).

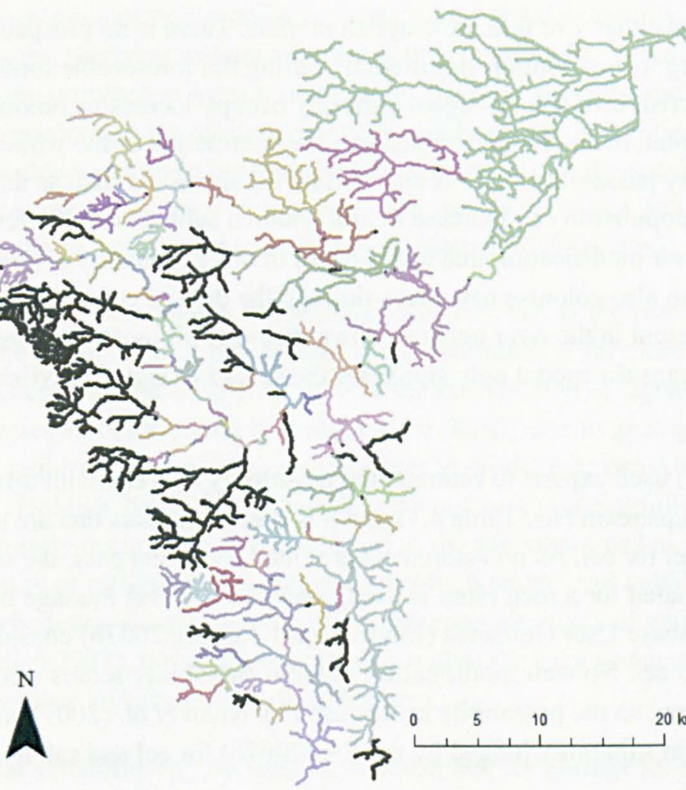


Figure 4.3. Each colour indicates a river subnetwork that is bounded by barriers. The charcoal coloured sections are those subnetworks with reservoirs or culverts longer than 200m downstream.

The barriers are indexed with the same unique identifier (i) as the subnetwork immediately upstream and is given a passability score (z). Species specific scores of 0 and 1 are given to barriers that are unpassable and fully passable respectively. Salmon and eel migrate into the catchment from the sea so they meet all barriers first in a downstream to upstream direction. In this direction all unmodified barriers are treated as being unpassable. This assumption is valid in the case of reservoirs as these are massive structures that are always unpassable to the focus species, but for culverts and weirs this will often be incorrect. In particular, small weirs can be ascended by large fish such as salmon. But as the dimensions of most weirs in the catchment are unrecorded then it is not possible to account for how weir sizes affect passability. However, as the weirs at the downstream end of the catchment are large and impassable, it is these that are key to determining the output of the model and so the assumption is fair and conservative.

Weirs can be modified with interventions such as fish passes to increase passability, but this does not usually lead to 100 % of a population of migrating species to be able to ascend from downstream to upstream habitat. Increased predation and competition at weirs, and a failure to find and utilise fish passes results in a proportion not being able to ascend (de Leaniz 2008). This is represented by giving z a species specific value intermediate between one and zero that reflects the proportion of a population expected to be able to ascend the weir for each fish pass type. z can then used to weight the quantity of habitat upstream of a weir by multiplying z and q together, giving a score that represents the relative value of habitat in each subnetwork. But as salmon and eel are migratory, then the cumulative effect of multiple weirs must be considered. How this is dealt with is explained shortly.

z is only treated as either 1 or 0 in the crayfish models. There is no prospect of white-clawed crayfish expanding its distribution significantly during the foreseeable future as it failed to do so before signal crayfish invaded. As signal currently occupy increasing amounts of potential white-clawed habitat, the model only considers the contraction of the white-clawed population. The use of a binary passability score is appropriate for signal crayfish as this species is non-migratory, and a population can increase *in situ* within a subnetwork if a few individuals gain access. For any weir modification that could result in this eventuality z was given the value of 1. Signal crayfish can also colonise new areas through the drift of eggs, and so it is assumed they are potentially present in the river network downstream of all locations where they have been recorded. This means the model only simulates the spread of signal crayfish in an upstream direction.

Nunn *et al.* (2007) used experts to estimate the passability of weirs with different fish pass types for eel migrating upstream (see Table 4.1) and it is these estimates that are used to provide the z values in the model for eel. As no estimate is provided for an eel pass, the same passability score as was estimated for a rock ramp is used, since the EA Fish Passage Improvement Prioritisation Database User Guidance (Environment Agency 2007b) considers both to be of equal suitability to eel. No weir modification specific passability scores were found in the literature for salmon, so the passability scores used by Nunn *et al.* (2007) are awarded based on the equivalencies in suitability judged by the EA (2007b) for eel and salmon.

Eel and salmon enter river systems from the sea, after which it is common that multiple barriers have to be ascended to reach habitat. To incorporate into the model the cumulative impact multiple barriers have on the proportion of a population migrating up the river network, the z values of every weir downstream of each subnetwork are multiplied together to create a cumulative passability score (c) for each subnetwork. This, rather than the z value of the downstream weir is multiplied by q as more appropriate weighting for models for diadromous fish.

There is a high degree of uncertainty associated with the expert judgement of fish pass effectiveness used in Nunn *et al.* (2007). How these different values affect the outcome of the model is examined by exploring different z values of 0.99, 0.95, 0.9, 0.8, 0.7, 0.6 and 0.5. It should be pointed out that there are limitations with the use of the cumulative passability scores as weightings to represent the effect of multiple weirs on a migratory population. For example, it ignores the carrying capacity of habitat, where if this is low, even if a small fraction of a population arrives at some habitat, it might be enough to utilise it to its full potential, meaning there should be no penalty due to the effect of the weirs downstream.

Table 4.1. Fish pass passability scores for eel from Nunn *et al.* (2007).

Fish pass type	% passability
Pool & traverse	25%
Rock ramps	90%
Alaskan A	25%
Weir removal	100%
V notch	50%
Larinier	75%

For salmon and eel, an additional step is taken to account for habitat suitability. This is not done for either crayfish species. Decision makers are mainly interested in the presence or absence of the invasive signal as the presence of even a single individual can cause the extinction of a white-clawed population through the introduction of crayfish plague. In addition, it is likely that signal crayfish will be able to colonise most of the Don Catchment, as the species is highly adaptable with regard to what habitats it can occupy (Schuster *et al.* 2010), being found in streams, canals, rivers, lakes, ponds, and even brackish water (NNSS undated).

There was no need to map habitat quality for white-clawed crayfish in the Don Catchment either. In contrast to signal the distribution of this species in the catchment is far more localised, occurring only in patches of habitat (Fig 4.2). Prior to the introduction of signal crayfish, the distribution of the species across England is thought to be largely due to geology and water quality as the species requires relatively calcareous water to produce its exoskeleton and is sensitive to pollution (Holdich 2003). These variables do not vary meaningfully within the patches of habitat currently occupied by white-clawed in the catchment and as so are not relevant. The availability of refugia and shelter provided by boulders and cobbles, overhanging banks, and large woody debris are also known to be important attributes of white-clawed crayfish habitat (Holdich 2003), but it was not feasible within the time frame of this work to collect data on the presence and absence of these features.

The estimate of habitat suitability (h) are used as an additional weightings for the subnetworks, so that zc is multiplied by h. The output of the model can then be expressed as the total quantity of habitat a species has access to in the catchment as a proportion of the total habitat potentially available (Ω):

$$\Omega = \frac{\sum_{i=1}^{n} q_i c_i h_i}{\sum_{i=1}^{n} q_i h_i} \tag{4.1}$$

4.2.2 Discriminating between habitat suitability for eel

The estimate of habitat suitability for eel was derived using expert judgement as there is a lack of data on the habitat preferences of this species published in the literature (Knights *et al.* 2001). Eel are relative generalists, exploiting all benthic habitats (Freyhof, & Kottelat, 2010). But as some habitats are more productive than others (Knights *et al.* 2001), and there are a wide range of habitat types available in the Don Catchment, it is therefore worth differentiating between them.

Nunn *et al.* (2007) identified distance of habitat from the tidal limit, water quality, river productivity and, habitat diversity as determinants of habitat quality for eel for which surrogate data was available for their study of the Humber region. As these variables are consistent with what was found about habitat usage by eel in the literature in this study, then these variables were also used to estimate relative habitat quality in the Don Catchment.

Though eel are particularly tolerant to water quality problems (Knights *et al.* 2001), the issue is still considered to be potentially significant in the UK (Aprahamian & Walker 2009). For example eel may be detrimentally affected by especially low DO and high unionised ammonia concentrations (Knights *et al.* 2001). Therefore the use of EA Chemical General Quality Assessment (GQA) grades by Nunn *et al.* (2007) as an indicator of habitat quality is appropriate. Knights *et al.* (2001) speculate that eel benefit from eutrophication as they thrive in habitats with a high trophic status and plenty of vegetation cover. As phosphorus is a key nutrient determining productivity then the choice of Phosphorus GQA grades by Nunn *et al.* (2007) as an indicator of habitat quality is reasonable. To develop a measure of habitat diversity, Nunn *et al.* (2007) utilised River Habitat Survey (RHS) data, a protocol used in the UK to survey the physical characteristics of river reaches (Environment Agency 2003), using observations of substrate, flow type, macrophyte cover and degree of channel modification. This is logical as eel in common with many species are thought to utilise different habitat types during different life stages (Knights *et al.* 2001). The last measure Nunn *et al.* (2007) used to map habitat quality was distance upstream of the tidal limit. This is particularly appropriate as Ibbotson *et al.* (2002) have shown that this metric is very important in determining the distribution of eel through river catchments.

There are a couple of variables identified in the literature as being important in determining habitat quality for eel have not been used in this study. Low pH may have a negative impact on eel (Knights *et al.* 2001), but such conditions do not occur within the Don Catchment (EA, pers comm.). The eel stock recovery plan for Ireland considers the geological signature of river water to be important (DCNER 2008), though as ratios of different rock types within a catchment were used to compare different catchments, its scale was not applicable to the Don Catchment.

A questionnaire (see Appendix d) was sent to regional and national authorities on eel to elicit their judgement on the relationships between habitat quality and the predictive variables to provide the weighting h of habitat suitability for each subnetwork in the model. The exception was for the distance from tidal limit, where observational data of the relationship between biomass and the tidal limit recorded by Knights published in Williams & Aprahamian (2004) is used.

Two experts of five contacted filled in the questionnaire. Experts consulted were keen to stress that there was much uncertainty associated with their weightings, and one expert, while providing useful information, preferred not to offer any. The following reasons were stated for their uncertainty: (1) eel prefer different habitat types at different stages of their life cycle, different times year and even different times of the day e.g. young eel prefer dense vegetative cover while larger eels prefer more open water, (2) some of the RHS categories were so broad that they could potentially refer to a wide range of river characteristics e.g. the category bank reinforcement could mean loose boulders deposited by the river bank or a completely artificial concrete river bank, both with very different impacts on eel ability to find shelter, (3) there is still a fundamental lack of knowledge about the relationship between habitat attributes and habitat quality for eel. Therefore the habitat quality weightings derived from experts must be treated cautiously. Nevertheless, results of this process are acceptable as the habitat suitability weightings only need to be roughly indicative to improve the utility of the model, and there is every indication that this is the case. Firstly the distribution in habitat quality predicted by the expert weightings matches what is described in the literature. Eel benefit from highly productive habitats (Knights *et al.* 2001), and it is those areas of the Don Catchment typically considered to be most productive (i.e. slow flowing, eutrophic lowland waterbodies) that have the highest relative habitat quality. The predicted habitat quality also declines with distance from the tidal limit, matching observed patterns in eel abundance in catchments across the UK (Ibbotson *et al.*

2002). Secondly there is a correspondence between where a local expert believes the best eel habitat to be located and the results of the habitat quality mapping. Both suggest that the use of the expert weightings has increased the usefulness of the model.

4.2.3 Discriminating between habitat suitability for salmon

Atlantic salmon are more specific in their freshwater habitat requirements than eel; migrating from the sea to spawn exclusively in high energy rivers (Fleming 1997). Individuals use olfactory cues to return to the same rivers in which they hatched where they seek out reaches with the right velocity, depth and river bed substrate size to spawn (Hendry and Cragg-Hine 2003a). Additional factors that determine the quality of habitat for spawning is the supply of well oxygenated water flowing through the substrate (i.e. the substrate cannot be smothered in silt), moderate to good water quality, and the presence of pools and cover in the river downstream of the spawning habitat in which the migrating salmon can rest and shelter from predators (Heggenes *et al.* 1990). Upon reaching the right habitat females construct a depression in the substrate termed a redd in which they deposit and bury their eggs. Following hatching the juvenile salmon spend a year or more growing in freshwater habitats before entering the marine environment. Again, during the juvenile stage the right river velocity, depth, substrate, good water quality and an abundance of cover is very important (Armstrong *et al.* 2003). Habitat for juveniles must also be of close proximity and connected to spawning habitat so salmon fry can access it (Hendry *et al.* 2003a). Because the success of the spawning and juvenile stages of salmon life history are particularly dependent on the physical, chemical and biotic characteristics of a river, the utilisable habitat in the Don Catchment was mapped for these two life stages.

Armstrong *et al.* (2003) and Hendry *et al.* (2003b) reviewed the literature to find the ranges of environmental conditions salmon utilise for variables important in determining habitat quality, and these were investigated as to whether it was feasible for them to be mapped in the Don Catchment. These are presented in table 4.2 along with the decision as to why those not included in the modelling were excluded.

River depth, velocity and substrate were chosen as predictive variables, as other studies have demonstrated that with the same data available in the Don Catchment, modelling approaches can successfully map these variables. While these represent less than half of the variables presented in table 4.2, they are considered to be the most significant in determining habitat quality for salmon (Hendry *et al.* 2003a). The other variables relevant to habitat quality in the Don Catchment could not be mapped with an accuracy to justify their inclusion in the study. Doing so would have unreasonably ruled out habitat that met the depth, velocity and substrate criteria.

The suitability of river depth and velocity for aquatic organisms has been mapped using the hydrological modelling software ISIS (see the ISIS user manual at http://www.isisuser.com/docs/manuals/isis/ISIS.htm), taking advantage of the fact that these models have already been built for many river systems for the purposes of flood modelling (Brookes, Kumar, & Lane 2010). River substrate has also been predicted using landscape

Table 4.2. Variables considered for use in salmon habitat mapping.

Variable	Included in habitat mapping	If no, why?
River depth	Yes	-
River velocity	Yes	-
Substrate type (gravel, silt etc)	Yes	-
Depth of substrate in which to bury eggs	No	Considered unfeasible to map
Cover (to allow salmon to hide, keep out of sunlight, to limit river temperature)	No	Using map data to classify whether river bank has riparian woodland not useful to define availability of cover given scope of study[1]
Quality of macroinvertebrate community as prey	No	Macroinvertebrate GQA grades not useful to define quality of prey given scope of study[1]
Chemical water quality	No	Chemical GQA grades not useful to define water quality given scope of study[1]
Water pH	No	Streams with a pH too low (<4.5) only occur upstream of reservoirs[2]

[1] Personal communication with T Worthington at the University of Southampton
[2] Personal communication with EA staff at Templeborough

variables derived using GIS (Bizzi & Lerner in preparation). These approaches were followed after communication with the cited authors.

Several studies have recorded the velocity and depth conditions salmon have utilised for spawning and as rearing habitat (reviewed in Armstrong *et al.* (2003) and are presented in table 4.3). Therefore, as a hydrological model can be used to predict the flow conditions within a river channel, it is possible to map the distribution of flow and depth that matches the conditions salmon have been observed to utilise as spawning and rearing habitat across a catchment (Brookes *et al.* 2010). This was done using the hydrological model ISIS.

ISIS predicts river flow based on the spatial dimensions of a series of river channel cross sections with elevations and hydrographs representing the input of water into the river channel. The ISIS model used was 1D; describing changes in flow longitudinally down but not across the river channel. Additional calculations produced by S Lane and C Brookes working on the River Model project as part of the University of Sheffield's URSULA project are made to distribute the velocities and depths across the river channel using river channel dimensions and the 1D output of ISIS. This is achieved by splitting the ISIS cross sections into subsections, for which the depth and wetted perimeters can be calculated. The 1D flow predicted by ISIS is then scaled for each of the subsections (see Appendix e for details).

The distribution of velocities and depths across a river cross section are then be used to measure the quantity of channel width within the range of velocity and depth conditions salmon have

Table 4.3. Reported flow conditions used by Atlantic salmon for spawning or as rearing habitat (Armstrong et al. 2003).

Life stage	Variable	Range
Spawning	Water velocity	15 – 80 cm/s
	Water Depth	17 – 76 cm
Rearing habitat	Water velocity	5 – 120 cm/s
	Water Depth	5 – 70 cm

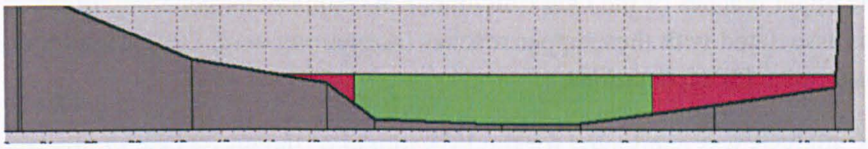


Figure 4.4. A cross section upstream of Lady's Bridge in Sheffield. The green area shows the proportion of channel that has water velocity and depth suitable for salmon to use to spawn under the modelled flow conditions.

been observed to utilise (see Figure 4.4). As the ranges used to map utilisable flow conditions are composed of the minimum and maximum velocity and depth observations, it is likely that the modelling is conservative in that it captures the extremes of what salmon can use. This reduces the chances of missing suitable habitat.

Channel cross sections used in ISIS are unevenly spaced along the length of a river, typically with a distance of 10 to 100 m between them, dictated by the need to capture changes in channel dimensions. Each river reach between ISIS cross sections is given the mean utilisable channel width of the bounding upstream and downstream cross sections, and multiplied by its length to create a relative measure of habitat quantity. The ISIS models did not comprehensively cover the entire river network in the Don Catchment, though they include most rivers in which a member of the fisheries team at the EA thought might contain suitable spawning habitat (N Trudgill pers. comm. Fisheries Officer at the EA). However, it is likely that spawning habitat will occur beyond the extent of the model.

Webb *et al.* (2001) found that in their Scottish study stream, salmon spawned during high flow conditions, which in terms of mean annual flow exceedance was within the range of Q50 and Q5, mostly occurred at flows intermediate between these two figures. This is in agreement with other literature which reports that salmon tend to spawn in high flow conditions (e.g. Gibbins *et al.* 2002). Therefore a Q20 input flow was used in the ISIS modelling. Juvenile salmon are found in rivers year round so median flow conditions (Q50) are chosen as being most appropriate for this life stage.

The flows used in the hydrographs taken directly from the flow duration curves for three gauging points in the Don Catchment; Hadfields Weir in Sheffield, Masbrough Weir in Rotherham, and a point near Crimpsall Sluice in Doncaster. The flow data for the period between 1960 and 1971 is published online in the National River Flow Archive at http://www.ceh.ac.uk/data/nrfa/index.html. The relative magnitudes of the hydrographs used in the ISIS models built for flood modelling are then used to portion the CEH flows.

Salmon construct their redds in the middle of the river channel (de Gaudemar, Schroder, & Beall 2000). Some ISIS cross sections, particularly at the lower end of the catchment, had flow and depth conditions utilisable for spawning at the margins of the channel, but were too deep within the centre of the channel. It is assumed that this marginal habitat is unsuitable for spawning, and so it was not included in the analysis.

Screening out cross sections that are bisected by unsuitable habitat has the effect of greatly reducing the quantity of spawning habitat predicted to be available, and mainly restricts this habitat to the upper reaches of the Don Catchment. As salmon are generally reported to spawn in conditions associated with these upper reaches (Armstrong *et al.* 2003; Hendry *et al.* 2003b), then this conforms with expectations.

A sensitivity analysis was conducted for the ISIS model of the upper Don to investigate how different flows within the Q5-Q50 range affected the distribution and quantity of predicted habitat (Appendix f). The results of the analysis show that individual ISIS cross sections, and the overall quantity of habitat in the upper Don are sensitive to the flows used in the hydrographs. The Q40 flow produced 50% less utilisable habitat compared to the Q20 flow, while the results of the other flows were more similar to that produced using the Q20 flow. Despite this sensitivity, the Q20 flow will probably produce reliable results for two reasons. Firstly, the Q20 flow is likely similar to the median flow conditions salmon experience while spawning. Secondly, at a catchment scale, the model will not be too sensitive to different flows (e.g. the upper Don will always have more habitat than the lower Don under a wide variety of flow conditions). However, if the model is to be used to manage habitat at a smaller scale, the results of the sensitivity test do indicate that a variety of flows are best used.

River substrate is an important determinant of habitat quality for salmon, particularly for spawning, when gravel beds are required for redd construction (Hendry *et al.* 2003b). Many variables determine the pattern of substrate along the river continuum, some of which can be measured using GIS. Bizzi *et al.* (in preparation) conducted a cluster analysis using the variables of Strahler and Shreve numbers (measures of stream order), river gradient, area of flood plain, and stream power (measure of the ability of a stream to transport substrate) to predict erosion or deposition features.

A similar approach was adopted to predict substrate in the Don Catchment using Bayesian and Neural Network statistical analyses. RHS data for the Humber Region was used to train the models in these machine learning approaches. However, an acceptable predictive success was not obtained, with the exception perhaps of the substrate type of cobble (see Figure 4.5). Both the Bayesian and Neural Network analyses had low success rates in predicting validation data, and substrate distributions did not match what was expected. This was most likely due to the large amount of noise in the RHS data. The hydromorphology of a river is a major determinant of the nature of its substrate, and so the hydromorphological classification conducted by the EA of the Don Catchment for the Water Framework Directive (WFD) was investigated for clues as to the distribution of substrate. Unfortunately almost all of the focus river reaches have been classified as either artificial or heavily modified in the Don Catchment (see Figure 4.6) meaning this information could not be used to differentiate between substrate type.

As personal knowledge was held of the rough distribution of substrate in the Don Catchment, a map was created of those areas where it was felt with high confidence the substrate was

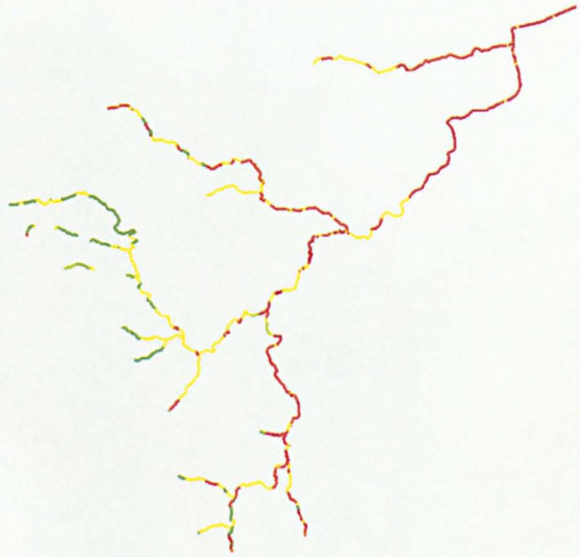


Figure 4.5. Predicted distribution of cobble. Green equals more likely, red less likely.

unsuitable for use by salmon for spawning (i.e. silt or clay) (see Figure 4.6). Where flow predicted as utilisable for spawning by ISIS overlapped with unsuitable substrate then this habitat was re-classed as unsuitable. This is only done during habitat mapping for salmon spawning as juvenile salmon can exhibit a high degree of plasticity with regards to the habitat they will utilise (Klemetsen *et al.* 2003). No weightings of habitat suitability are used for salmon so the variable h is not required in eq 4.1 and q is the quantity of habitat per subnetwork predicted by the ISIS modelling, rather than the length of river. The connectivity models for eel, salmon and crayfish can be found on the CD that comes with this thesis.

4.2.4 Scenario analysis of weir modification options

To demonstrate how the models developed in this chapter can be used to explore different weir modification options, they are used to compare the outcomes of five scenarios to open up the Don Catchment. In addition to the *status quo* scenario (Figure 4.7), four other weir modification scenarios are analysed that differ widely in the number of weirs modified. The first is fish pass installation up the Don and then up the Rother (the Rother scenario; Figure 4.8), the second up the Don and then the Loxley (the Loxley scenario; Figure 4.9), the third up the Don to its upper reaches (the Don scenario; Figure 4.10), and the fourth concentrates on multiple weirs in the lower half of the catchment (the lower catchment scenario; Figure 4.11). For simplicity's sake, it is assumed that the weirs are modified so they are passable to all of the focus species.

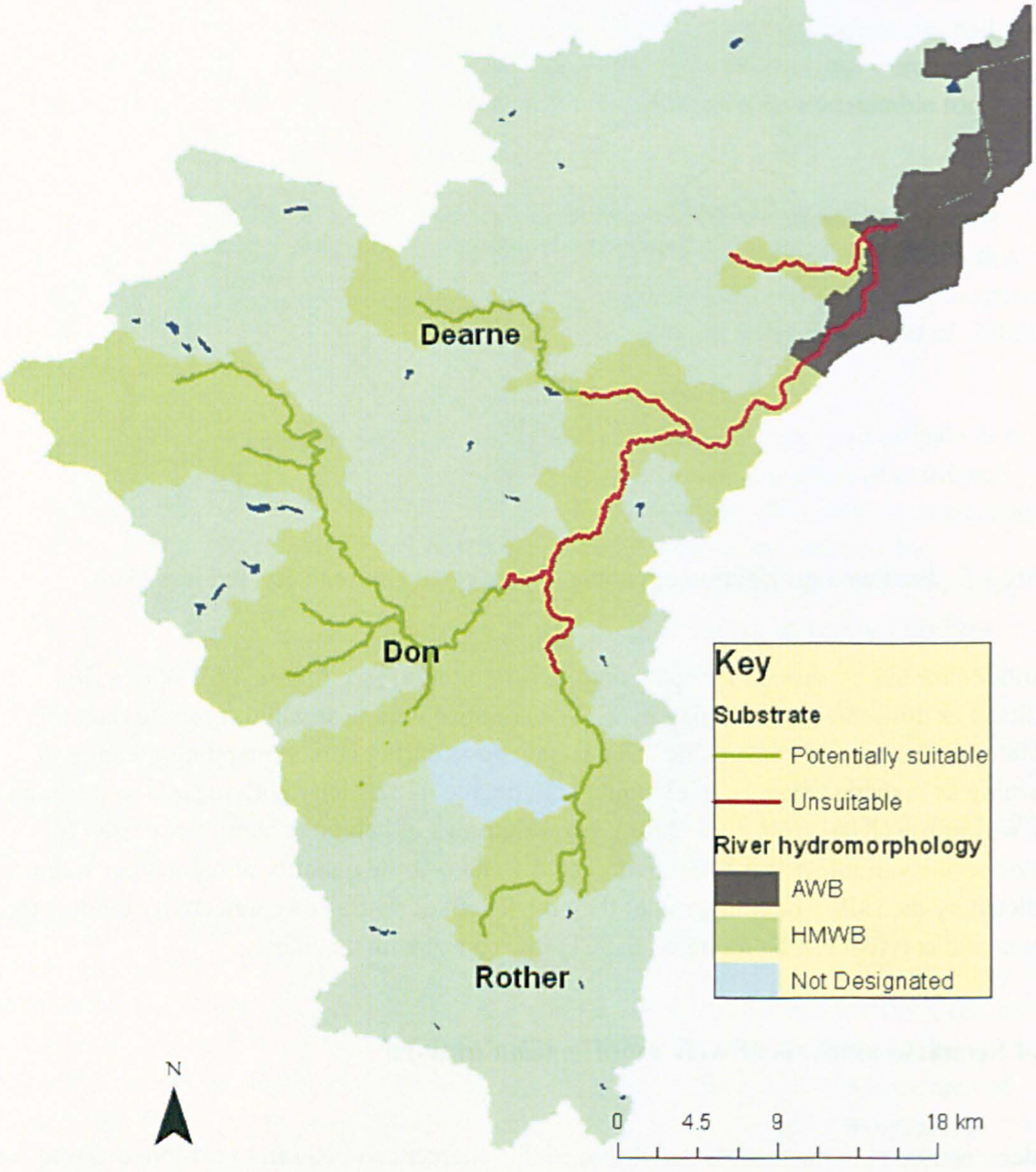


Figure 4.6. Expected distribution of potential substrate for spawning denoted by river colour, and the Water Framework Directive (WFD) hydromorphological status of the rivers denoted by subcatchment colour. It is the opinion of members of the Catchment Science Centre, the University of Sheffield, that the river reaches marked as unsuitable are highly likely to consist of silt, sand or clay and consequently cannot be utilised by salmon for spawning. In the WFD classification, AWB stands for artificial water body, HMWB stands for heavily modified water body, and not designated means that this water body is yet to be classified.

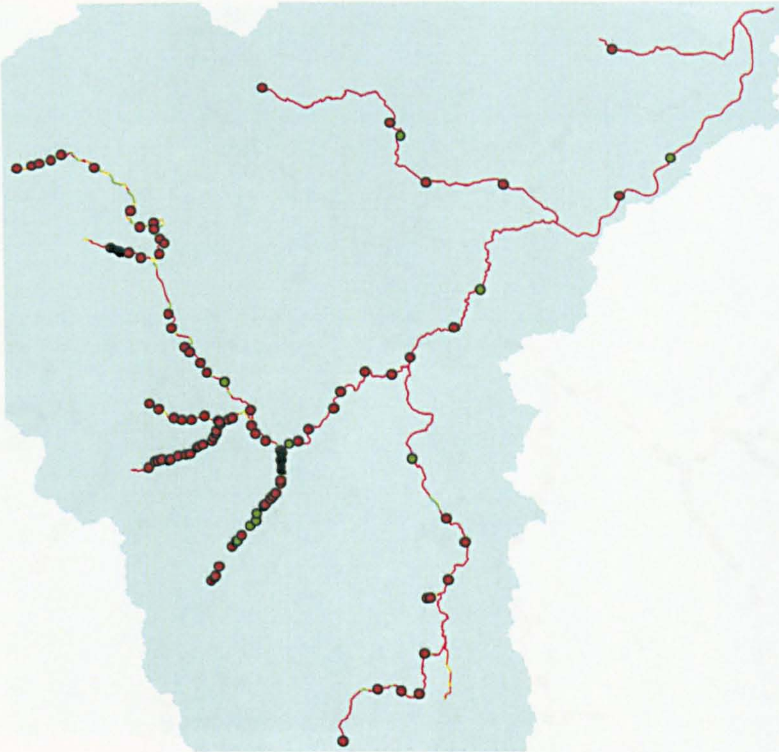


Figure 4.7. The current distribution of weirs with connectivity enhancements in the Don Catchment.

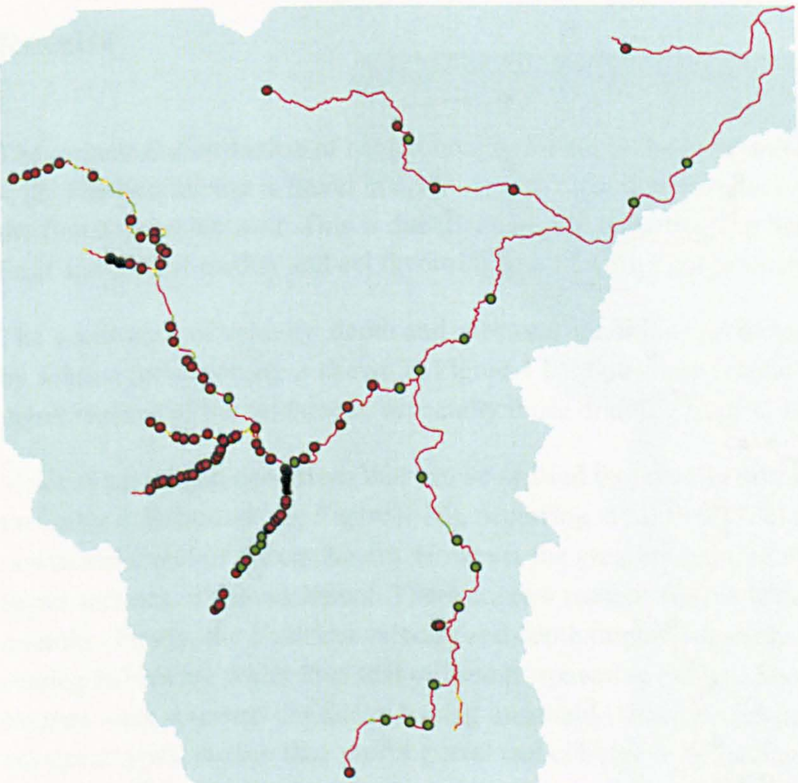


Figure 4.8. The distribution of weirs that are modified in the Rother scenario.

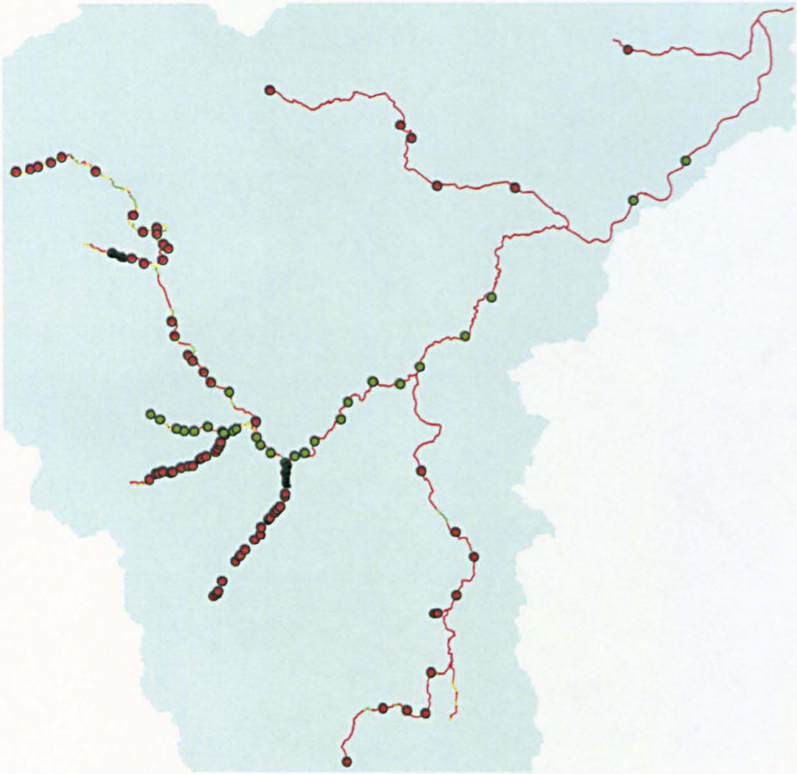


Figure 4.9. The distribution of weirs that are modified in the Loxley scenario.

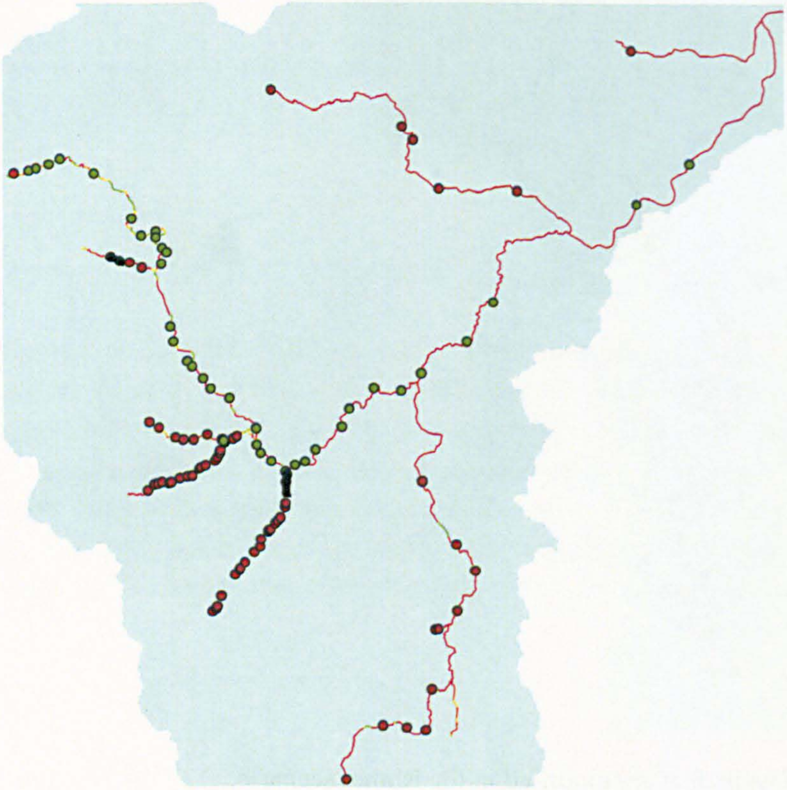


Figure 4.10. The distribution of weirs that are modified in the Don scenario.

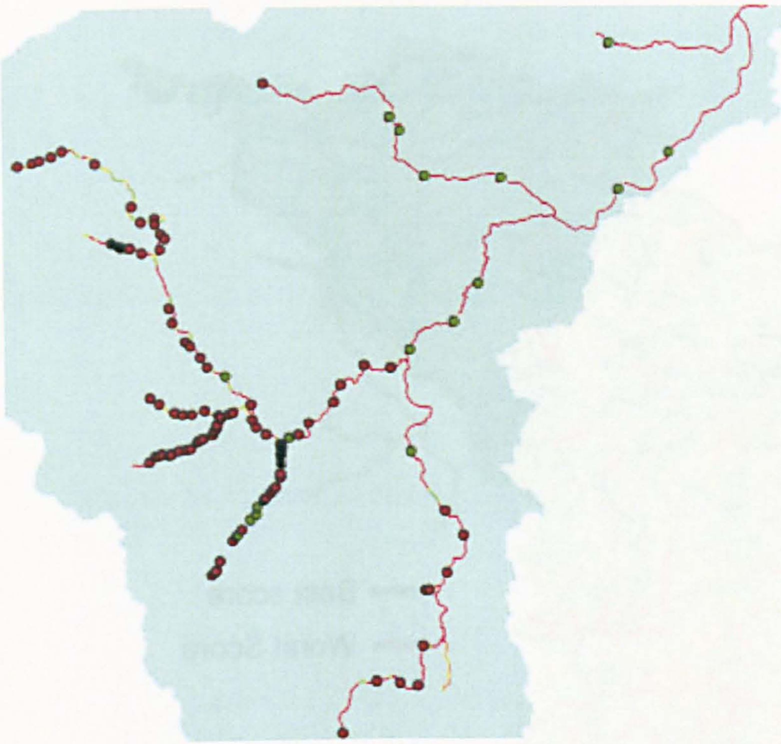


Figure 4.11. The distribution of weirs that are modified in the lower catchment scenario.

Results

The estimated distribution of habitat quality for eel in the Don Catchment is presented in Figure 4.12. The best habitat is found in north-eastern most downstream end of the catchment, below the first unpassable weir. This is due to the negative relationship between distance from tidal limit and habitat quality and eel favouring habitat with high to intermediate P GQA scores.

The occurrence of velocity, depth and substrate conditions predicted to be potentially utilisable by salmon for spawning is shown in Figure 4.13. Spawning habitat occurs predominantly in the upper reaches of the catchment, especially those draining from hills in the west.

Velocity and depth conditions that can be utilised by juvenile salmon as rearing habitat have a far wider distribution (see Figure 4.14), occurring in all rivers including those at the downstream end of the catchment. However the greatest quantity is again concentrated in the upper sections of the catchment. There are two reasons for the wider distribution and greater quantity. Firstly, the observed velocity and depth ranges salmon have been observed to utilise as rearing habitat are wider than that utilised as spawning habitat. Secondly for this life stage no reaches were screened out due to having unsuitable substrate (as juvenile salmon can occupy all substrate types, though they prefer gravel and cobble) or by having the channel bisected with unsuitable flow conditions.

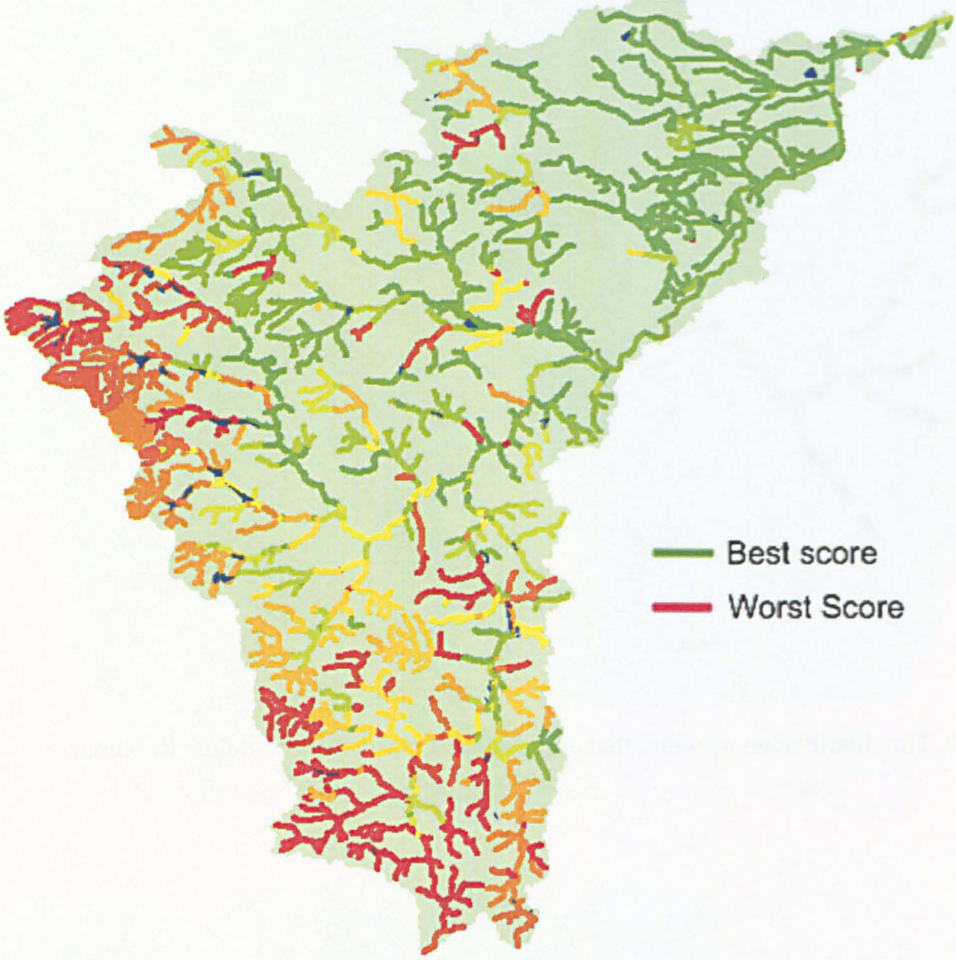


Figure 4.12. Estimated habitat quality in the Don Catchment for eel.

The cumulative effect of multiple weirs with fish pass installed was found to be extremely important in determining the proportion of a migrating population in reaching habitat (see Figure 4.15). There are over forty consecutive weirs on the River Don. Eleven weirs must be ascended before the first reach with flow conditions modelled to be within the range utilisable by salmon for spawning is reached. If more than 50% (a figure chosen for illustrative purposes rather than for ecological significance) of a migrating population of salmon is to reach this habitat then the mean effectiveness of the fish passes downstream must be around 95% or greater. If the mean is 90% of a migrating population, then only 30% will reach the habitat. The majority of the salmon spawning habitat on the River Don is located between the 24th and the 31st weirs. For fish passes with an effectiveness of 99%, approximately 80% of the salmon population would reach the 24th weir, whereas a fish pass effectiveness of 95% would only allow 30% of the salmon population to reach this weir.

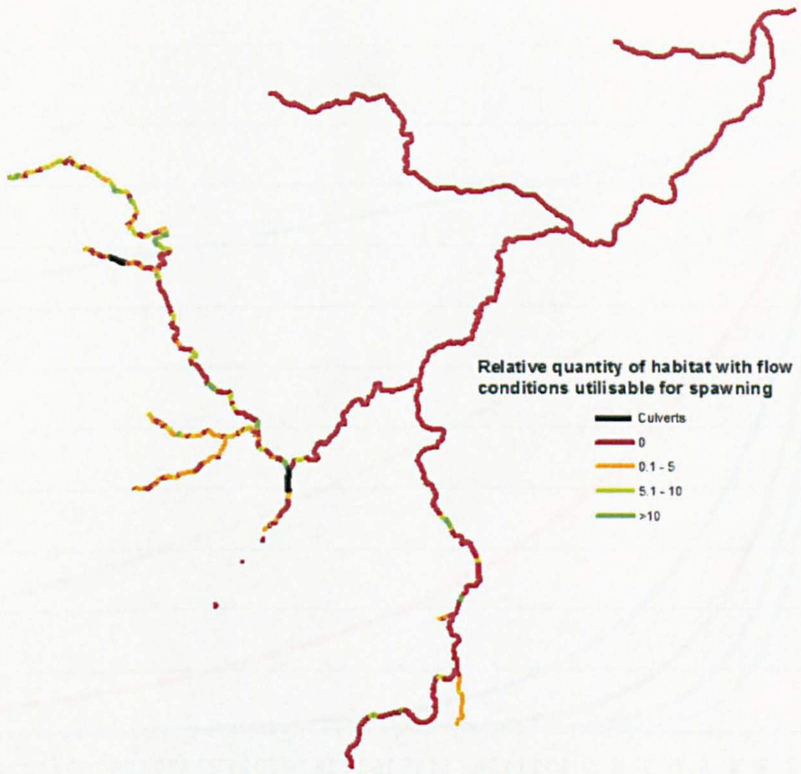


Figure 4.13. Distribution of habitat with predicted velocity and depth conditions within the range salmon can utilise for spawning, screening out areas where substrate is thought unlikely to be suitable.

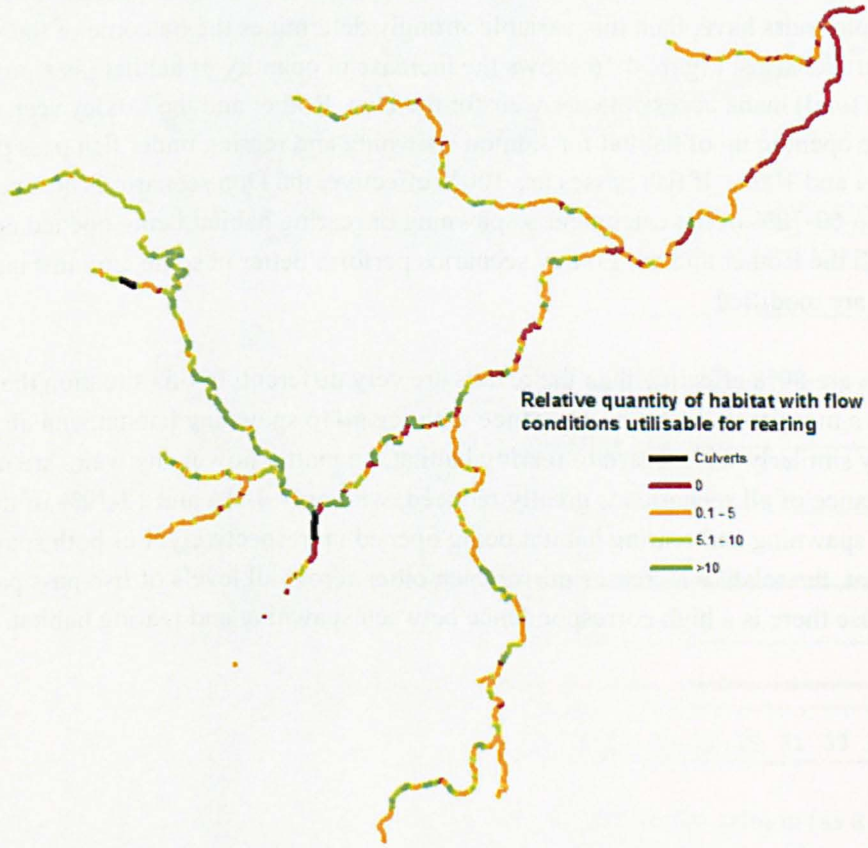


Figure 4.14. Distribution of habitat with predicted velocity and depth conditions utilisable as nursery habitat.

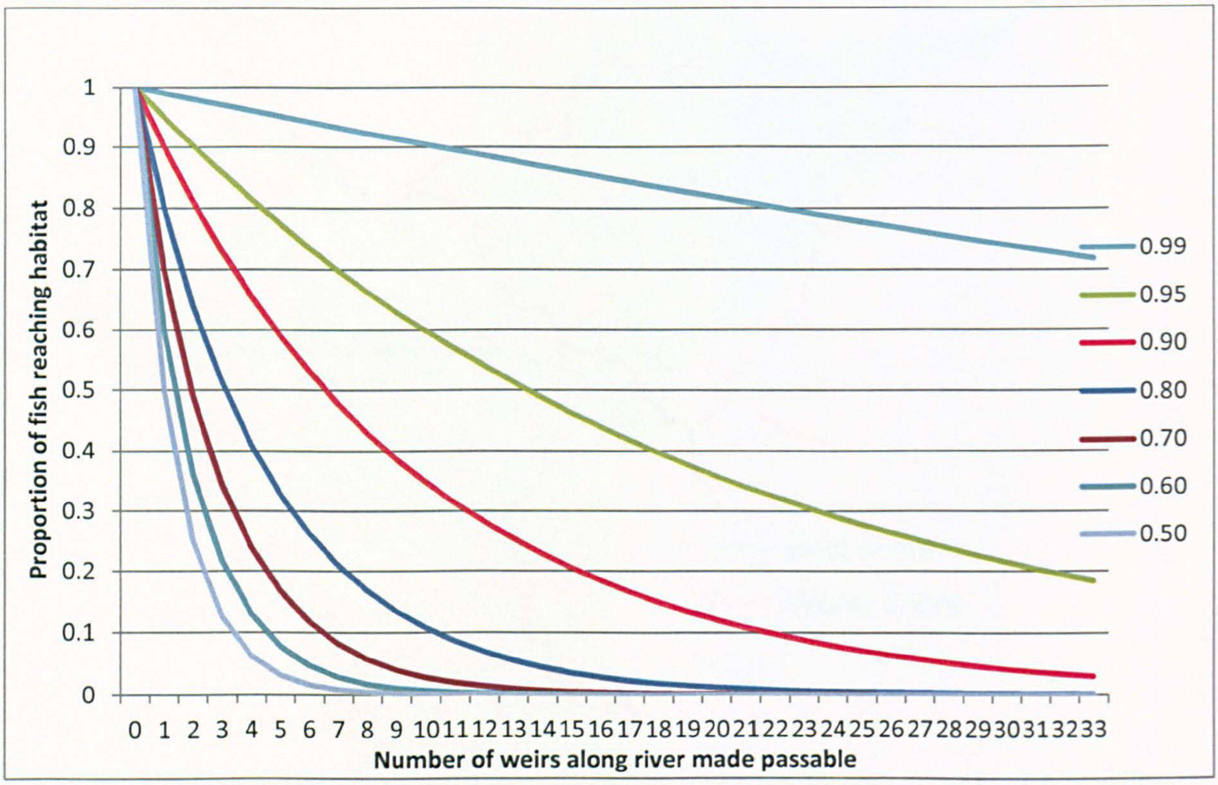


Figure 4.15. Cumulative impact of downstream weirs on the proportion of a population of migrating fish reaching habitat under seven different weir passability scenarios.

Because the different levels of fish pass effectiveness have such a big impact on the cumulative effect multiple weirs have, then this variable strongly determines the outcome of the weir modification scenarios. Figure 4.16 shows the increase in quantity of habitat (as a proportion of catchment's total) made accessible per weir for the Don, Rother and the Loxley scenarios with regard to the opening up of habitat for salmon spawning and rearing under fish pass passabilities of 80%, 95% and 100%. If fish passes are 100% effective, the Don scenario is best performing with between 60-70% of the catchment's spawning or rearing habitat being opened up to salmon. Both the Rother and the Loxley scenarios perform better in some circumstances when fewer weirs are modified.

If fish passes are 80% effective then the results are very different. In this situation the Rother scenario has a marginally better performance with regard to spawning habitat, and all scenarios perform very similarly with regard to rearing habitat, no matter how many weirs are modified. The performance of all scenarios is greatly reduced, with only 4-5% and 18-19% of the catchment's spawning and rearing habitat being opened up respectively. For both spawning and rearing habitat, the relative increases mirror each other across all levels of fish pass passabilities. This is because there is a high correspondence between spawning and rearing habitat.

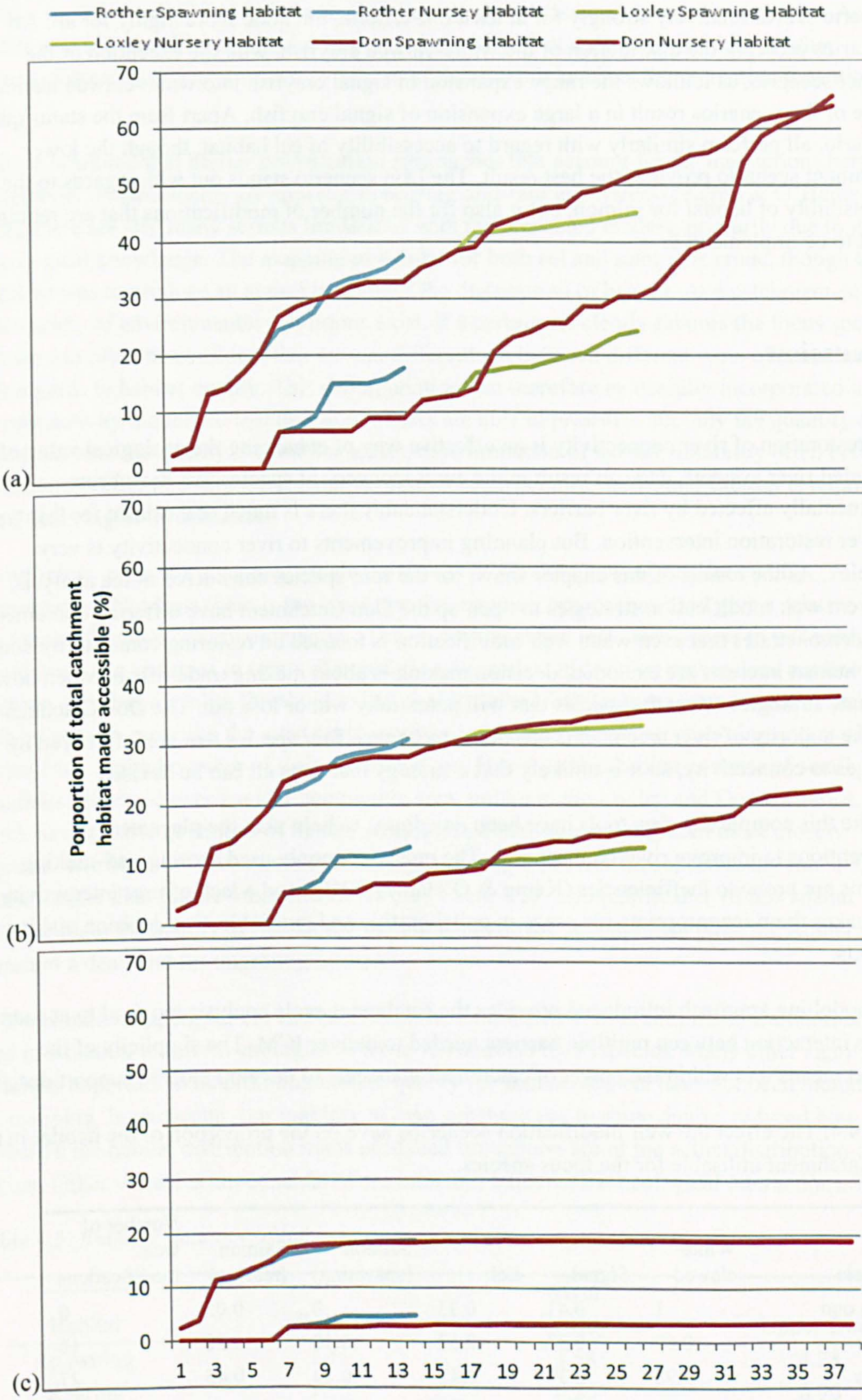


Figure 4.16. Increase in quantity of spawning and rearing habitat for salmon (as a proportion of catchment's total) made accessible per weir for the Don, Rother and the Loxley scenarios for the fish pass passabilities of (a) 80%,(b) 95% and (c)100%.

The consequences for the four focus species of the five scenarios are shown in table 4.4. Each scenario scores relatively strongly for at least one criteria, but none score highly for all. All scenarios preserve the distribution of the white-clawed crayfish, with the exception of the Rother scenario, as it allows the range expansion of signal crayfish into white-clawed habitat. None of the scenarios result in a large expansion of signal crayfish. Apart from the status quo scenario, all perform similarly with regard to accessibility of eel habitat, though the lower catchment scenario provides the best result. The Don scenario stands out with regards to the accessibility of habitat for salmon, but it also for the number of modifications that are required for it to be implemented.

Discussion

The restoration of river connectivity is an effective way of enhancing the ecological value of degraded river systems, and can result in the swift recovery of species that have been detrimentally affected by river barriers. Understandably there is much enthusiasm for this type of river restoration intervention. But planning improvements to river connectivity is very complex. As the results of this chapter show, for the four species considered in the analysis, different weir modification strategies to open up the Don Catchment have differing outcomes. This demonstrates that even when weir modification is focused on restoring connectivity and other human interests are excluded, decision making is about making trade-offs between how alternate strategies affect the species that will potentially win or lose out. The Don Catchment like the majority of river catchments has many more than four species that are influenced by changes to connectivity, so it is unlikely that a strategy that suits all can be devised

Despite this complexity, few tools have been developed to help plan the placement of interventions to improve river connectivity. The most commonly used scoring-and-ranking systems are prone to inefficiencies (Kemp & O'Hanley 2010), and a lack of user interactivity that makes them inappropriate for usage in collaborative and multiobjective decision making contexts.

The modelling approach introduced provides the catchment-scale analysis required to account for the interaction between multiple barriers needed to deliver ICM. The simplicity of the method means it is within the power of catchment managers to develop tools to support decision

Table 4.4. The effect the weir modification scenarios have on the proportion of the habitat in the Don Catchment utilisable for the focus species.

Scenario	White-clawed	Signal	Eel	Salmon (spawning)	Salmon (rearing)	Number of weir modifications
Status quo	1	0.41	0.33	0	0.05	0
Rother	0.69	0.33	0.57	0.18	0.38	16
Loxley	0.98	0.39	0.47	0.24	0.45	27
Don	1	0.34	0.53	0.66	0.64	38
Lower catchment	1	0.4	0.62	0.15	0.41	15

making. Once built for a single species, the system can be expanded to incorporate additional species, so that the decision maker can consider the trade-offs between multiple species. As the models provide real-time feedback, then they can easily be coupled with models of other impacts of weir modification, such as how modification might affect the recreation potential of rivers.

While it is argued that barrier prioritisation approaches that account for the interactions between connectivity enhancements are superior to scoring-and-ranking systems (Kemp & O'Hanley 2010), there are still many serious limitations with the presented models, primarily due to gaps in ecological knowledge. The mapping of habitat for both eel and salmon is crude, though the objective was to produce an approximation of the distribution of habitat. At a catchment-scale, a wide variety of environmental conditions exist. If a certain set clearly favours the focus species, then we can often be confident that we can differentiate between different parts of a catchment with regards to habitat quality. This differentiation can therefore be usefully incorporated into the connectivity models so that decision makers are able to prioritise not only the quantity of habitat but also the quality. At smaller scales, discrimination of habitat suitability often becomes increasingly difficult as environmental variation becomes more subtle, and caution is required when factoring in its influence.

Nevertheless, even at a catchment-scale the results of habitat mapping require careful interpretation. Not least there is the issue that the mapping approaches used give a relative indication of habitat quality or quantity. This is not translated into what access to this habitat would mean for a species in terms of population dynamics. A decision maker does not know for example, whether a quality threshold exists, that if passed, habitat turns from source to sink. The Rother scenario produces the most rapid increase in quantity of salmon spawning and rearing habitat for a limited number of weir modifications. However this habitat consists of small quantities dispersed over a wider geographic area, unlike in the Loxley and Don scenarios, which have greater quantities of habitat concentrated between weirs spaced more closely together. The mean relative quantity of habitat per length of river is proportionally much lower on the Rother than for the other two rivers (see Table 4.5). The significance of this spatial distribution to the quality of habitat for salmon is unknown. It could mean that the Rother may represent a dead end for migrating salmon.

As the habitat mapping for eel and salmon in the Don Catchment is simplistic, it should not be used in isolation to inform strategies to try to re-establish these species. Many other significant variables important in determining habitat quality for salmon and eel have not been included in the mapping. In particular, our inability to map substrate has to some degree reduced how reflective the habitat distribution maps produced for salmon are of the actual distribution of habitat. Other variables not considered are inter and intraspecific ecological interactions. For

Table 4.5. Relative quantity of habitat per length of river.

	River		
Habitat	Rother	Loxley	Upper Don[1]
Spawning	1.11	3.58	4.28
Rearing	5.13	6.25	8.90

[1] From the confluence with the Loxley to the upper reaches.

example signal crayfish are potential predator of salmon eggs, and there are anecdotal reports that this biotic interaction is causing a decline in salmon populations in other UK Catchments (D Newton pers. comm.), though evidence for this has not been found in laboratory experiments (Gladman *et al.* 2011).

The chapter has also demonstrated the high sensitivity the outcome of fish migrations have to the cumulative effect of weirs with partially passable fish passes. This is of great significance to decision makers as it dictates what type of weir modification strategy will be most successful in opening up habitat to migrating species. A small variation in passability results in very different modification strategies being appropriate. Even with high passability rates, schemes to open more than a few consecutive weirs could well be ineffectual. In such circumstances weir removal rather than fish pass installation may be required if connectivity in heavily modified catchments is to be restored. Decision makers must consider the not insignificant question of what proportion of a migrating population needs to be able to reach spawning habitat for the population to be sustainable.

These results also have implications with regards to what is the most appropriate way for migratory species to be re-established in impounded catchments. Several papers note that small numbers of salmon tend to enter catchments to spawn different to the ones in which they were hatched, and suggest that this unassisted recolonisation may make stocking superfluous (Perrier C. *et al.* 2010; Griffiths *et al.* 2011). However, immigrants tend to arrive in relatively low numbers, so the migration may be whittled down by the cumulative effect of fish passes resulting in numbers not great enough to establish a sustainable population. In such circumstances, it may be necessary to actively stock a migratory species, so that numbers that manage to return are great enough to maintain a viable population.

It is for these reasons that future research on tools to help decision makers plan river connectivity enhancements should prioritise the generation of ecological knowledge. This modelling approach can deliver ICM, but its usefulness is restricted by the lack of information on aspects of ecology, such as the effectiveness of different fish pass types for the fish species found in the Don Catchment. This information is critically important in determining the output of the models.

Conclusions

The planning of interventions to restore river connectivity is difficult due to the vast number of options that often face decision makers. The results of this chapter show that decision making is made even more complex by demonstrating that the connectivity needs of multiple species do not necessarily overlap, meaning trade-offs between competing interests must be made. The modelling approach introduced in this chapter provides a tool than can be used interactively by decision makers to explore in real-time how strategies to open up river networks create habitat accessibility for multiple species. Two major sources of uncertainty in the modelling approach are in the mapping of habitat quality for the focus species and the cumulative effect multiple barriers have on the migration of species. Uncertainty in habitat quality is less of an issue as the model can be constructed in a conservative manner by only ruling out habitat that we are certain is unfit for the focus species. Thereby habitat is not erroneously ruled out and the decision maker is not unnecessarily restricted in their options. Uncertainty in the cumulative effect of weirs on the other hand is a big issue as it exponentially increases with the number of barriers, meaning small changes in the estimates of the passability of individual weirs can have a big impact on the output of the model. For this reason expert estimates of the passability of weirs are not appropriate, and empirical studies that can be used to build models to accurately estimate weir passabilities are urgently needed. A striking result of the study is that the cumulative effect of multiple weirs that even a high proportion of fish can ascend still quickly whittle down a migrating population to negligible numbers. This has great significance for hydropower schemes being built on existing weirs in the UK as the result will often be series of fish passes up river catchments. Even highly effective ones may not be sufficient to allow sustainable levels of fish to migrate.

5 Construction of the Weir Tool

5.1 Introduction

Models are important tools that can be employed to help achieve better outcomes in the process of catchment management decision making. They are useful in that they can facilitate the development of a shared understanding between people involved in the decision making process, predict how different management options will fare with regard to criteria of interest, find optimal solutions given management constraints and help identify management priorities (Caminiti 2004).

The potential for models to aid catchment management has long been recognised. But it was during the digital revolution of the 1950s and 60s that enabled significant progress to be made, including the establishment of the Harvard Water Program and Stanford Watershed Model (Singh 2002; Reuss 2003). Ever since, the exponential increase in computing power has driven the development of ever more sophisticated models.

The world as a single system is too complex to model in its entirety, and so modellers instead reduce reality down into simplified sub-systems that determine the processes they are interested in e.g. sediment transfer, overland flow of water, population dynamics. The implementation of Integrated Catchment Management (ICM) requires that multiple such models of all the economic, environmental and social interests affected by potential management interventions (from now on referred to as decision criteria) are brought into the decision making process. Together these decision criteria can be used in a 'what if' analysis; the outputs of the models used to evaluate the performance of alternative catchment management options (Soncini Sessa *et al.* 2007).

The usage of multiple models in this way can be inefficient and overwhelming if the decision maker must interact with each independently. Consequently the models required to conduct ICM are often packaged into a single tool known as a Decision Support System (DSS). DSS have a graphical user interface (GUI) in which the user can specify catchment interventions and then receive outputs from the decision criteria models in a manner that is easily interpreted (Jakeman & Letcher 2003; van Delden *et al.* 2011). van Delden (2011) identifies some of the qualities common to DSS:

- able to support policy-relevant questions
- pay particular attention to long-term problems and strategic issues
- aim to explicitly facilitate group interaction and discussion
- apply in complex and ill-structured or wicked decision domains, characterised through a large number of actors, factors and relations, a high level of uncertainty, and conflicting interests of the actors involved
- are user friendly in entering input, viewing output and analysing results
- incorporate actual data and process knowledge from different disciplines
- operate on different scales and resolutions where required

- may be fully dynamic with feedback loops between individual models built as a flexible component-based system that can be extended with additional modules over time

A DSS will not necessarily have all these qualities, but rather it is the catchment management problem the DSS must address and the users it is targeted towards that determine what features it requires. The design of a DSS must account for the nature and scale of the decision problem, the data and information available, modelling requirements, time constraints for producing an assessment and the stakeholders involved (Jakeman & Letcher 2003). In this chapter a DSS dubbed the Weir Tool, designed to aid weir modification decision making is introduced. The chapter begins by examining the purpose and the target users of the Weir Tool. It continues by describing the functional and then the architectural design of the tool and finishes with a brief discussion of some of the implications of the choices made during its development.

5.2 The function of the Weir Tool

van Delden (2011) suggests that the first questions that should be asked at the outset of the construction of a DSS are who are the users going to be, what are they going to use it for, and how will it help decision making? These questions were asked during the design of a DSS built to aid the selection and placement of modifications to weirs. The Weir Tool, as it is called, was built to be used by three user groups; people who have been given the responsibility to make decisions with regard to weir modifications (e.g. staff at the Environment Agency), those who are stakeholders in the management issue of weir modification (i.e. those who have an interest the ecosystem services identified in chapter 2), and participants of an experiment introduced in chapter 6. The Weir Tool is directed towards stakeholders as a user group because their involvement alongside conventional decision makers is required if fair and effective decision making is to be delivered (Soncini Sessa *et al.* 2007). Therefore the Weir Tool should be designed so that all stakeholders are able to understand and utilise it. However, producing such an inclusive tool is not an easy task. Stakeholders encompass people with such a wide range of technical ability, from highly trained individuals to those who have had little formal education, so that in reality it is more appropriate to think about making the Weir Tool accessible to as large a proportion of stakeholders as possible. Consequently the Weir Tool was designed to be user-friendly; requiring no advanced scientific or technical training beyond standard schooling in the UK. However, the planning of weir modifications, as with most catchment management issues, is inherently difficult and multifaceted, and a DSS that functions adequately to support decision making will inevitably be complex. Therefore it is likely that the Weir Tool will exclude some stakeholders.

The main purpose of the Weir Tool is to permit stakeholders and decision makers to conduct a 'what if' analysis, by allowing them to assess how different modification options affect multiple stakeholder interests. Because to do this it requires the use of models, then it falls into the category of a model-driven DSS as opposed to one of the other four categories of DSS; communications-driven, data-driven, document-driven and knowledge-driven (Power & Kaparthi 2002). One way DSSs can be employed to deliver 'what if' analyses is by finding the range of management interventions that optimise the criteria the decision makers desire to maximise, thereby producing a pre-calculated range of optimal options for the decision maker to explore. This approach has not been taken as it tends to obscure the complexities and dependencies in the DSS, reducing transparency (Jakeman & Letcher 2003). Transparency is important in building decision maker and stakeholder trust in DSSs, and enables users to understand how they works, essential if they are to be used appropriately. Furthermore, DSSs are usually constructed using assumptions and imperfect knowledge, which stakeholder input can correct or improve upon. An optimisation approach reduces the potential for stakeholder involvement in the operation of a DSS and therefore may inhibit stakeholder feedback on the functioning of the tool. For these reasons, the Weir Tool was developed to work as an exploratory tool. This approach allows stakeholders to try out different weir modification options on the fly; quickly refining strategies given the DSS evaluation of their choices. This requires that the running speed of the DSS is quick enough for the stakeholders to interact with so they have time to try out different options, and that they do not become frustrated by waiting for feedback. This necessitates that exploratory DSSs such as the Weir Tool are composed of models that are not computationally demanding (van Delden *et al.* 2011).

The Weir Tool is a prototype; demonstrating how a DSS that can aid weir management decision making could be built and used. The construction of a fully functioning DSS that integrates models of all a holistic set of evaluatory criteria such as the framework of ESs identified in chapter 2 is a time consuming and labour intensive task (van Delden *et al.* 2011; Lerner *et al.* 2011), beyond the scope of a PhD project. Therefore the Weir Tool incorporates models encompassing a subset of chapter 2's ESs, presented in table 5.1. DSSs do not need to provide spatially explicit information (e.g. Ticehurst *et al.* 2007). But, as was demonstrated in chapter 4, accounting for the interdependencies between weirs is of vital importance, and so the Weir Tool must aid its users to this end.

Table 5.1. Criteria modelled in the Weir Tool with which weir modifications can be assessed. The microhydro model is introduced in appendix a, the eel, signal and white-clawed models in chapter 4, and the canoeing models in chapter 2. Note that the salmon model was constructed after the weir tool, and so has not yet been integrated into the Weir Tool.

Name of decision criteria displayed in the GUI	Definition	Unit of measurement
Microhydro output	Hydroelectricity produced by all the microhydro schemes installed	MWh
Eel	Habitat in the catchment accessible to European eel (*Anguilla anguilla*) as a proportion of the total potentially available	%
Signal	Proportion of the catchment that has been colonised by the invasive signal crayfish (*Pacifastacus leniusculus*). (Indicator goes down as the crayfish spreads)	%
White-clawed	Habitat remaining occupied by the native white-clawed crayfish (*Austropotamobius pallipes*) as a proportion of the current range. (Indicator goes down as habitat is lost)	%
Fun	The quality of the Don Catchment's weirs as a resource of fun for canoeists	Value between 1 (max) and 0 (min)
Danger	The danger the weirs of the Don Catchment pose to canoeists	As above
Cost	Cumulative cost of all weir modifications specified by the user	£

Unlike many other DSSs however, the Weir Tool is not temporally explicit. The connectivity models (chapter 4) do not attempt to simulate how weir modification will affect the populations of the focus organisms as too little is known about the ecology of these species to predict such dynamics. Likewise, the hydroelectricity yield of microhydro schemes will vary through time because of the influence of climate change on river flow, but this is not considered as it is not known how the climate will change. Therefore it is not necessary for the Weir Tool to consider temporal change.

5.3 Design of the Weir Tool

The Weir Tool allows a 'what-if' analysis of the effect of different weir modification scenarios in the Don Catchment on six decision criteria of interest to decision makers. There was not enough space in the graphical user interface in which to define each decision criteria, so an indicative name was used, while the exact definition was provided in a document that explains what the tool is and how it works. There are three components the Weir Tool requires if it is to deliver a 'what if' analysis; models for each of the decision criteria, a database within which information about the weirs in the catchment is stored and a GUI with which the user can interact and receive information from the models and database.

The Weir Tool is targeted at a wide range of users of all technical ability, so the GUI was designed to be relatively easy to use (see Figure 5.1). A minimal amount of text is displayed and the decision criteria are presented as graphics. This was also one of the reasons a web-based approach, that requires that the GUI is displayed and interacted with in a web browser, was chosen as being appropriate (Power & Kaparthi 2002). Many people, including most decision makers and the students recruited to take part in the experiment presented in chapter 6 are familiar with web browsers and website controls such as the use of hyperlinks to navigate between web pages. Therefore, the utilisation of web browser software would make the tool more intuitive than if novel controls were created. Web-based DSSs also have a number of additional advantages. They provide access to freely available web services such as online mapping tools that can be incorporated into the tool. Taking advantage of the availability of these is more efficient than programming bespoke functions. Also, a web-based DSS can be used by geographically distributed users. These strong advantages of taking a web-based approach to decision support are why most new DSSs are web-based (Power & Kaparthi 2002).

The Weir Tool GUI has two webpages, the main being the catchment overview webpage. As the spatial position of weirs in a river network is an important factor determining the placement of weir modifications, it was essential that the catchment overview page included a map pane (see Figure 5.1a), displayed in which are a polyline of the river network and markers of the locations of weirs in the Don Catchment. The user is also provided with buttons that allow two types of information about the weirs to be displayed; how passable the weirs are for different fish groups, and the locations of weir modifications.

(a)

(b)

Figure 5.1. The GUI of the Weir Tool. a) The catchment overview. b) The form with which weir modifications can be specified.

Information on the performance of the current combination of weir modifications with regard to the decision criteria are presented in two formats. Firstly there is a rose diagram which displays two values for each decision criterion. A red line indicates how the catchment performs as it is with its current combination of weir modifications. This provides a benchmark to the green segments, which indicate the value of each criterion under the weir modification scenario the user has entered. The green segment increases in size if the value of the criterion is increased by a modification, and shrinks if the value is decreased. A rose diagram was chosen over a radar graph as the area within a radar graph is not just dependent on the values of the decision criteria but also on their relative positioning around the graph (see Figure 5.2). As a larger area can be perceived as indicating a better performance, then this effect can bias how the user interprets the decision criteria. The absolute values of all of the decision criteria are presented in a table, as the rose diagram displays the relative values to communicate change and how the decision criteria trade-off.

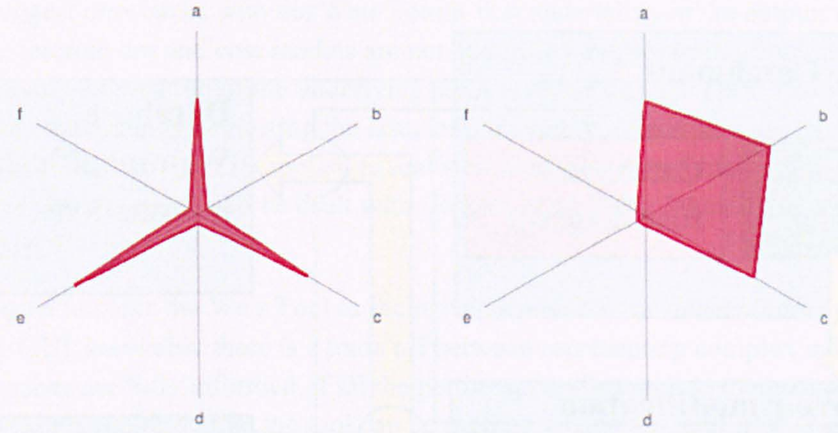


Figure 5.2. An example of how placing the same values in different positions on a radar graph can result in radars with very different areas.

To interact with the GUI to enter a weir modification scenario into the Weir Tool, the user clicks one of the markers in the map pane that denote the locations of the weirs. This brings up a 'balloon' containing attributes of the weir and a hyperlink to the second GUI webpage which holds a menu of weir modifications (see Figure 5.1b). Here the user can specify what modifications they wish to apply to this weir. Also displayed are another rose diagram and table showing how the decision criteria are affected by modifications to this weir alone. For example, how much hydropower would be generated by the installation of a microhydro on this weir, rather than the cumulative value for the whole catchment.

So that a catchment strategy designed by a user of the DSS is not lost or undone by later users, a user login system was developed. Each user is provided with a unique login ID that permits the Weir Tool to record and store details of the weir modifications made in a user specific database. This database is then returned to when the user re-logs on. A master login also allows the current status of the weirs in the Don Catchment to be updated.

5.4 Computing architecture of the Weir Tool

A conceptual model of the structure of the Weir Tool is shown in Figure 5.3. The GUI of the Weir Tool is displayed in a web browser, and is scripted using Hypertext Markup Language (HTML) and the server-side scripting language PHP. The map pane of the GUI uses the free web mapping service application Google Maps, embedded in the GUI using the scripting language JavaScript and the Application Programming Interface (API) of Google Maps. Rendered in the map pane is a bird's eye view of the Don Catchment that can be displayed as either satellite imagery or as cartographic information. Google Maps also provides the standard web mapping controls of zooming in and out and moving the view. The rose diagram was also produced using a free web service application Google Charts. This was achieved by adapting and embedding the Google Charts radar graph using its API and JavaScript.

Data on the attributes of the 229 weirs in the Don Catchment are stored in a database hosted on the server of University of Sheffield. To render the river network and weir locations in the map pane, data is downloaded from the server database and processed by code in the web browser to

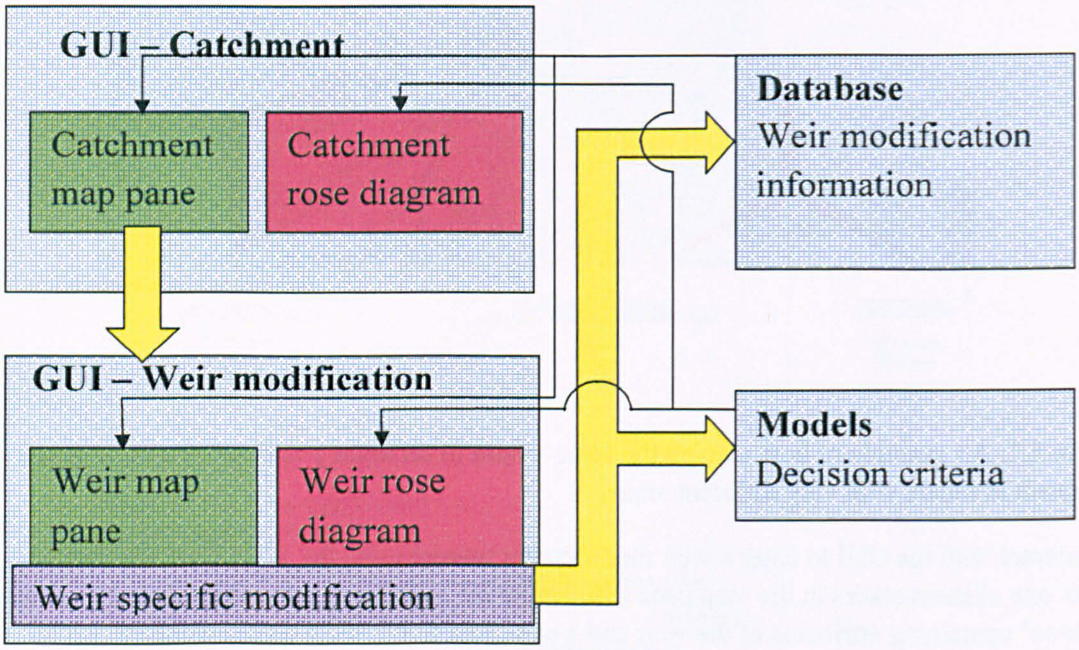


Figure 5.3. Conceptual diagram of the architectural structure of the Weir Tool.

create a Keyhole Markup Language (KML) file encoding geographical data, which can be displayed in Google Maps.

When the user specifies a weir modification or uses the buttons on the GUI to change how the weirs are displayed, the web browser translates this interaction into Structured Query Language (SQL), which is used to query and edit the server database. The models of the decision criteria are connected to the DSS using ActiveX controls. These allow the software in which the decision criteria models run to be controlled through the web browser. ActiveX controls are available for Excel 2007 in which the connectivity, hydropower, and cost models run, and Netica, in which the canoeing models run. The only web browser that has ActiveX functionality is Internet Explorer, restricting the use of the Weir Tool to this software. The decision criteria models do not interact, meaning that it is not required that they are coupled, and each can be controlled independently from the web browser. The Weir Tool is available on the CD that comes with this thesis.

5.5 Discussion

The Weir Tool DSS presented in this chapter offers a way for stakeholders and decision makers to quickly and conveniently explore the outcome of different modification options in the Don Catchment. To the knowledge of the author, this is the first DSS built to use multiple criteria to aid weir management. However, many other DSS have been produced to support other catchment management issues. The technical elements used in the tool are not unique, but perhaps the exact combination is; each component being chosen as being best suited for the task of planning weir modification strategies.

One of the biggest drawbacks with the Weir Tool is that uncertainty in the outputs of the habitat connectivity, microhydro and cost models are not quantified and communicated through the tool. This is essentially a limitation of the underlying models rather than the DSS. The Weir Tool is a prototype and consequently neglecting the issue of uncertainty does not matter, but if the Weir Tool was a fully functioning DSS applied to real weir management problems then it is very important that uncertainty should be dealt with (Rogers *et al.* 2000; Jakeman & Letcher 2003; Holzkämper, *et al.* 2012).

It was attempted to make the Weir Tool as inclusive as possible for stakeholders by giving it a user friendly GUI. Inevitably there is a trade off between representing complex information to DSS users so they are fully informed of all the pertinent details required to make good decisions and keeping things simple so that the tool can be used by a large range of people as possible. Only by exposing the Weir Tool to a wide range of stakeholders will reveal how user friendly and inclusive it really is.

An advantage of the Weir Tool is that it is very easy to apply to other catchments. In principle, as long as there is data available to build the decision criteria models, then there is no reason why the tool cannot be transferred to another catchment. Additionally, the Weir Tool can be easily expanded by incorporating models of other decision criteria, provided that they can be coded into the web browser, or run in software that has ActiveX capabilities. The Weir Tool is also relatively cheap to produce; utilising mainstream software and freely available web services, though the downside of the latter is that they could be discontinued at anytime. Being web-based brings a few other disadvantages; a tool can be overloaded if too many users run it at the same time, web-based DSSs are vulnerable to malicious hacking (a risk if sensitive information is contained within the tool) and the web scripting languages are constantly being updated or becoming obsolete, resulting in web based tools themselves quickly becoming obsolete if not maintained (Power & Kaparthi 2002).

Lessons were learnt during the construction of the Weir Tool, so that if it was built again, some modifications to design would be made. Loading and running the connectivity, microhydro and weir cost models in Excel and the Netica canoeing models is computationally demanding, and causes a delay of a few seconds each time a user specifies a weir modification. Such a delay is well known to irritate users of software and is counterproductive to its usage. To improve the performance of the DSS, an alternative is for the models to be coded into the web browser. The canoeing Bayesian Network can also be speeded up by exporting and storing the conditional probability tables into the web browser, so that it is not necessary to load and run Netica every time the Weir Tool runs, allowing the tables to be referenced when a new weir modification is set. A couple of additional advantages will result from in transferring all the decision criteria models into the web browser. There will no longer be any need to use ActiveX controls, meaning the user is no longer tied to the internet browser Internet Explorer. Also, the Weir Tool will become an entirely web-based DSS, freeing it from the constraints of the computer it is run on e.g. the need to have Netica and Excel installed.

DSSs are commonly believed that their use leads to improved decision making. By making a holistic approach to the management of weirs, large quantities of information must be considered that can overwhelm the decision maker (Rogers *et al.* 2000). By considering the interdependencies of weir modifications, and multiple criteria, it is suggested that the usage of the Weir Tool can improve weir modification decision making. In chapter 6, an experiment is presented in which the utility of the Weir Tool to improve decision making is tested.

6 Testing the usefulness of the weir tool

6.1. Introduction

The management paradigm of Integrated Catchment Management (ICM) proposes a holistic approach to catchment management, advocating the treatment of the full range of stakeholder interests as management objectives in the decision making process (Mitchell & Hollick 1993). These are used together as a framework with which different potential catchment interventions can be evaluated and compared. One of the key benefits of this approach is that it makes explicit the conflicts and synergies between different management objectives, which is thought to improve the effectiveness of decision making (Jakeman & Letcher 2003). While ICM is widely advocated (Jamieson 1986; Mostert 1999; Pascual 2007), actually implementing it is highly challenging; requiring that the decision makers are able to predict how environmental, social and economic systems, often outside of their expertise, will respond to management interventions. Given that these responses are commonly affected by spatial and temporal interactions, and exhibit nonlinear dynamics (Liu *et al.* 2007), clearly ICM decision making poses a huge analytical burden, one that the human mind struggles to cope with, even when highly trained and working in teams.

It is therefore not surprising that since the advent of the digital age, researchers have sought to exploit the analytic ability of computing systems to construct Decision Support Systems (DSSs) that provide the predictive capability required by ICM (Reuss 2003; Singh & Frevert 2006). As time has progressed, increasingly sophisticated DSSs have been developed in ever larger numbers. However, this has not been reflected in the application of DSSs, which have a poor rate of uptake for use in catchment management (Argent *et al.* 1999). Barriers to utilisation include a lack of confidence in the predictive ability of DSSs and the high level of technical support required for operationalisation (Borowski & Hare 2007). It is sometimes assumed that if these hurdles are overcome, improved catchment decision making will follow (e.g. Lerner *et al.* 2011).

Yet this need not necessarily be the case. There are numerous mechanisms by which DSSs such as the Weir Tool could plausibly reduce the effectiveness of decision making. For example, the use of a computer screen as the medium of information exchange may be less stimulating for decision makers than more collaborative social approaches, or users may not be able to process and make use of the large quantity of information provided by a DSS. It is therefore vital that the assumption DSSs improve decision making is tested, so that it can be understood to what degree they aid decision making, and to provide insights into how they can be better designed and utilised.

To test whether the Weir Tool improved ICM decision making, an experiment was ran to compare hypothetical catchment management decisions made by a group using the Weir Tool to a control group that took a more conventional map and rule based approach to decision making. The objectives of this chapter are to:

- discuss how a DSS can be tested to see if it improves decision making
- introduce the design of the experiment set up to test the Weir Tool
- present the initial results, and plans for further analysis
- discuss the results and the implications for design and usage of DSSs

6.2. Method

6.2.1. How do you test whether a DSS improves decision making?

Some decisions made during the decision making process have a higher quality than others, that is to say they produce a more desirable outcome. To test whether one approach results in a higher quality of decisions than another, we must first have an idea of what decision quality is and how it can be measured. For the purposes of this study four interrelated aspects of a decision that form components of decision quality were identified. These are presented in the left column of table 6.1. In the right column are the ways a DSS could potentially aid the user so that these components of decision quality are improved.

Evidence that a DSS improves decision making can be looked for in both the decision making process and the decisions that result from it, and so observations can be made of both. Based on table 6.1 four hypotheses that were feasible to test in an experimental setting were derived:

Hypothesis 1- A decision maker's knowledge of an environmental issue is enhanced

One of the primary purposes of a DSS is to communicate information to a user that they did not already know, especially information that is unfeasible to easily obtain during conventional decision making methods (Westmacott 2001). Therefore it is predicted that the users of a DSS will gain a greater knowledge of an environmental issue than decision makers using conventional approaches.

Hypothesis 2 - The effectiveness of decision making is increased

By effectiveness of decision making it is meant how close is a decision to maximising the decision's management objectives. When there are multiple management objectives and numerous options in terms of management interventions, many potential decisions are suboptimal in that another potential decision exists that can improve at least one objective without causing a decline in any others. However, for some decisions, there is no way to improve one objective without causing a subsequent decrease in another objective i.e. causing a trade off. Such decisions are said on lie on the Pareto frontier (Soncini Sessa *et al.* 2007) (see Figure 6.1a). Therefore it is predicted that if a DSS results in more effective decision making, decisions that lie closer to the Pareto frontier will be observed (see Figure 6.1b and 6.1c).

Table 6.1. What is decision quality and how might a DSS improve it?

Components of decision quality	How might a DSS improve decision quality in ICM?
the degree to which stakeholder interests are maximised	by teaching the user about the catchment management issue
the extent to which environmental, social and economic processes underlying stakeholder interests are sustainable	by encouraging the user to do further learning e.g. after noticing knowledge gaps
how fair and equitable a decision is	by allowing the user to simulate the impact of interventions that are mentally difficult or impossible to estimate
how satisfied stakeholders are with a decision	by reducing error in the thinking of stakeholders
	by reducing the time taken for the user to understand the impact of an intervention
	by improving communication between stakeholders
	by increasing creativity in solving environmental management problems
	by increasing engagement and interest in an environmental issue

Hypothesis 3- Decisions are more moderate

By making the trade-offs between different management options explicit, a DSS will make the user more aware of potential inequalities and conflicts between stakeholders. Even when a decision maker is neutral, such as when making hypothetical decisions in an experimental context, it is predicted that a heightened awareness of trade-offs will result in more balanced decisions. It is expected that this will be evident in decision making with fewer extremes i.e. objectives given particularly high weightings (see Figure 6.1d).

Hypothesis 4 –Decision makers are more confident in their decisions

If a decision maker has a good ability to find the most effective decisions, it could be expected that they feel more secure about the decisions they have made. Therefore it is predicted that if a DSS has been successful in aiding its user, they are more likely to feel confident about their decisions.

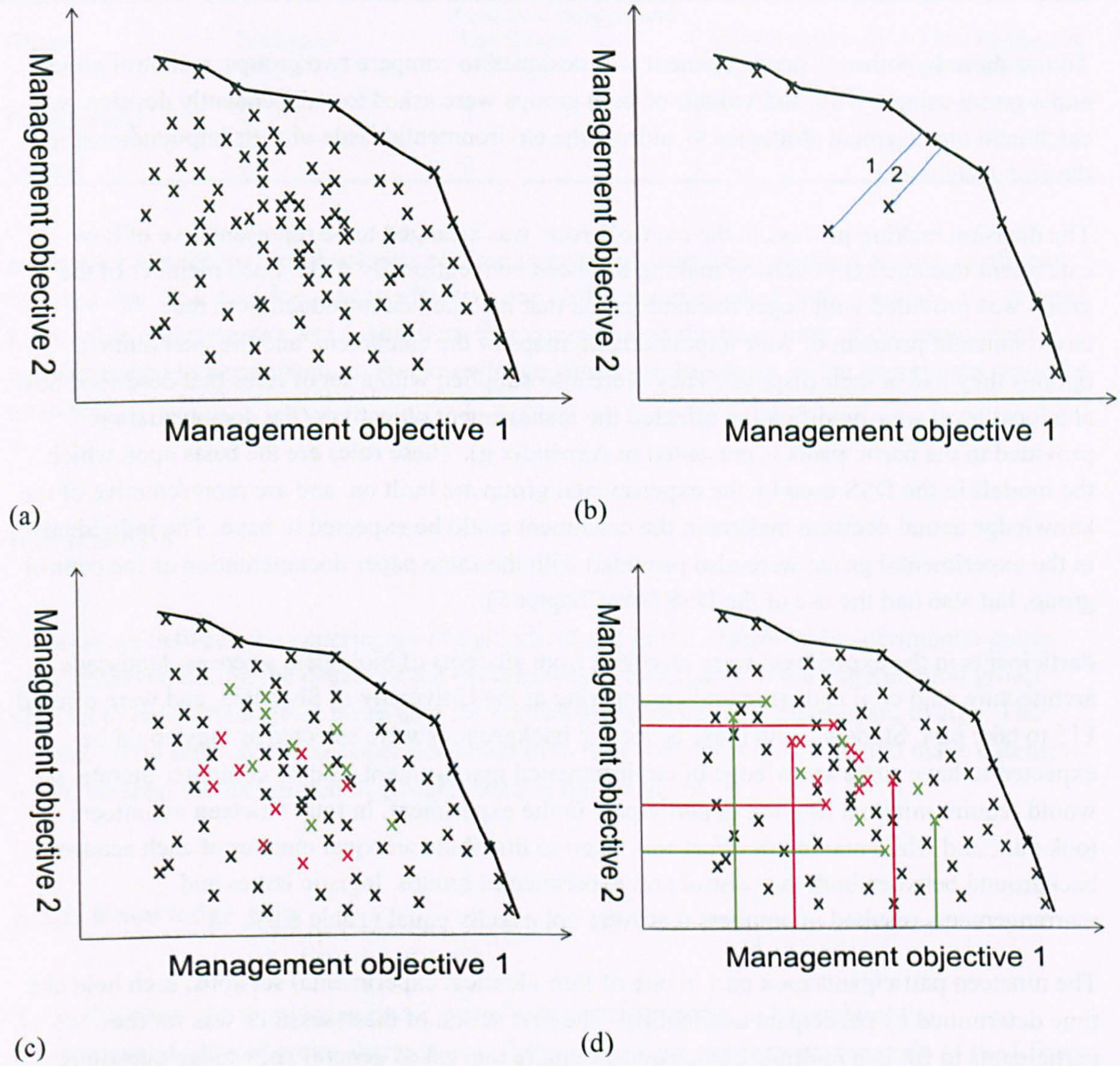


Figure 6.1. a) A hypothetical example of decisions (the crosses) plotted against their performance with regard to two management objectives. The area in which the decisions lie is termed the decision space. The line is known as the Pareto frontier and connects those decisions for which no improvement of one management objective can be made without trading off another. b) Distance from the Pareto frontier can be used to assess decision effectiveness, so that if a decision is closer to the Pareto frontier (1), it is more effective than one further away (2). c) Therefore it is hypothesised that decisions made using the Weir Tool (represented by the green crosses) will be closer to the Pareto frontier than those using conventional decision making methods (the red crosses). d) More moderate decisions will be more clustered in the decision space (the red crosses verses the dispersed green crosses), and have a smaller range with regard to how they perform against the management objectives. This is shown in the figure with the red and green lines indicating the maximum and minimum values for the corresponding red and green decisions. The red lines mark smaller ranges than the green lines, suggesting that the red decisions are more moderate.

6.2.2. Experimental design

To test these hypotheses, an experiment was designed to compare two groups; a control group and a group using a DSS. Individuals of both groups were asked to independently develop two catchment management strategies to address the environmental issue of weir impoundment in the Don Catchment.

The decision making process in the control group was arranged to be representative of how catchment management decision making has been conventionally done. Each member of the group was provided with paper documentation that included an introduction to the environmental problem of weir impoundment, maps of the catchment, and the intervention options they had at their disposal. They were also supplied with a set of rules that described how at a local level weir modification affected the management objectives (the documentation provided to the participants is presented in Appendix g). These rules are the basis upon which the models in the DSS used by the experimental group are built on, and are representative of the knowledge actual decision makers in the catchment could be expected to have. The individuals in the experimental group were also provided with the same paper documentation as the control group, but also had the use of the DSS (see Chapter 5).

Participants in the experiment were recruited from students of biological sciences, landscape architecture, and civil and structural engineering at the University of Sheffield, and were offered £15 to take part. Students with these academic backgrounds were selected as they could be expected to have some knowledge of environmental management, and be computer literate, so would require minimal training to participate in the experiment. In total nineteen volunteers took part, and while maximum effort was taken to distribute an equal number of each academic background between both the control and experimental groups, logistic issues and rearrangements resulted in numbers that were not exactly equal (Table 6.2).

The nineteen participants took part in one of four identical experimental sessions, each held at a time determined by participant availability. The first action of these sessions was for the participants to fill in a multiple choice questionnaire that asked general knowledge questions about the environmental management issue of weir impoundment and modification, as well as a Likert item question that asked how much knowledge they had about this issue. This set a baseline of how much knowledge each participant had on the issue. Next a presentation was given to introduce participants to the weir issue and an exercise was run to familiarise participants with the materials they had been provided with. Participants then completed two exercises where they were challenged to come up with a weir modification strategy for two hypothetical management scenarios. These exercises were to develop weir modification strategies in the Don Catchment with the following two aims:

- to maximise hydroelectric output and eel habitat accessibility with a budget of £3m.
- to maximise all management objectives with a budget of £1.5m (this budget was initially £6m, but it became apparent during the first session that they were not going to be able to spend all this money).

A further £15 was offered as a prize for the individual that developed the best strategies to incentivise participants to take the exercises seriously. The details of the plans were recorded in pre-structured spreadsheets on laptops provided to each participant. Each time a participant

Table 6.2. Academic background of participants across the experimental and control groups

Group	Academic background			
	Biological sciences	Landscape architecture	Civil and structural engineering	Total number of participants
Experimental	4	3	3	10
Control	5	0	4	9

completed an exercise, feedback was elicited through a Likert item question on how confident they felt that their decision was an effective one. After completion of both exercises, the general knowledge questionnaire and Likert item first completed at the beginning of the experiment were re-issued to participants so that knowledge gain over the course of the experiment could be assessed.

6.3 Results

Differences between the experiences of the individuals in the control and experimental group were observed during the course of the experiments. Participants in the experimental group seemed to enjoy themselves more than the control group, who were often heard to sigh. The control group scrutinised the paper documentation they were provided with and made extensive notes, whereas the experimental group tended to ignore theirs.

6.3.1. Knowledge gain

To analyse how the knowledge participants believed themselves to have about the environmental issue of weirs changed over the course of the experiment, the scale of the Likert item was allocated numerical scores (see Figure 6.2). The results are shown in table 6.3. Both groups started with a very similar belief that they had a low level of knowledge, typically around 'little'. The perceived gain in knowledge was also the same between groups, believing by the end that they had an 'intermediate' or 'reasonable amount'.

In the case of the multiple choice questionnaire that tested for an actual increase of knowledge about the issue of weir impoundment over the course of the experiment, results are presented in table 6.4. Pre-experiment the Weir Tool group performed slightly better than the control group but the difference was not significant (Two sample $t(28)=1.25$, P = n.s.). The post-experiment questionnaire revealed both groups were much more successful in answering the questions correctly, demonstrating they had gained knowledge. However, when the proportion of correct answers per question was compared between groups, the control group showed a significantly larger increase in knowledge (Paired two sample $t(14)=-2.98$, $P<0.001$).

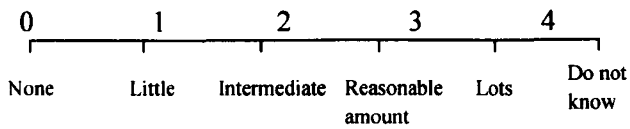


Figure 6.2. The numerical scoring of the Likert item used when participants were questioned about the depth of knowledge they had on the environmental issue of weir impoundment, and how much confidence they had in the decisions they had made during the experiment. No respondents selected the null category.

6.3.2 Confidence in decision making

As with perceptions of knowledge, the Likert item participants were asked to fill in to measure confidence in the decisions they made during the experiment was numericised. The confidence of the participants was typically between 'intermediate' and a 'reasonable amount', across both groups and exercises. There was not a significant difference between the groups for either of the exercises (exercise 1: Two sample $t(13)= -1.67$, P=n.s.; exercise 2: Two sample $t(13)= -1.73$, P=n.s.).

6.3.3. Decision effectiveness and moderateness

To test the hypothesis that use of the Weir Tool resulted in more effective decision making, the distance of the decisions made by both groups from the Pareto frontier were compared. This required that the Pareto frontier be calculated for all the decisions that could potentially be made with the Weir Tool. There are a number of different methods by which Pareto frontiers can be

Table 6.3. Change over the course of the experiment in knowledge participants believed they had about the environmental management issue of weir impoundment.

	Perceived knowledge at start		Perceived knowledge at end	
Group	Mean	Median	Mean	Median
Experimental	0.9	1	2.5	3
Control	0.77	1	2.5	3

Table 6.4. Change in the proportion of questions answered correctly in a multiple choice questionnaire about the environmental issue of weir impoundment over the course of the experiment

Group	Mean proportion of correct answers at start	Mean proportion of correct answers at end
Experimental	0.4	0.69
Control	0.31	0.82

derived (Kuby *et al.* 2005). The 'brute strength' method is simply to calculate all the different decision options in the decision space. However this can only be done if the number of decisions that can potentially be made is low enough that all of their positions can be computed (Anjaneyulu & Manickam 2006).

Therefore, to know if a brute strength approach was feasible, it was necessary to calculate how many different decisions could potentially be made using the Weir Tool. To do this the following equation was developed:

$$X = WM + \sum_{n=2}^{W} M^n \frac{(W+2-n)(W+1-n)}{2} \tag{6.1}$$

Where X is the number of potential decisions that can be made, W is the number of weirs in the catchment (229) and M is the number of combinations of potential modifications per weir (54433). Eq 6.1 tackles the problem of calculating the number of weir modifications that can be made by the Weir Tool by breaking it into a sequence; the number of potential modifications if a single weir is modified, the number of potential modifications if two weirs are modified, and so on until all potential groups have been calculated. These can then be summed. The single weir is represented by the term WM. For the groups of weirs, two terms need to be considered. The number of permutations of modifications for a set of weirs (the term M^n), and the number of combinations each set of weirs can be assembled out of the total number of weirs (the term $\frac{(W+2-n)(W+1-n)}{2}$).

For the Weir Tool, equation 1gives the number $\sim 10^{1099}$ for the potential decisions that can be made, a number that is much greater than the number of particles is in the observable universe, which is believed to be $\sim 10^{80}$ (Penrose 1989).

For this reason, the brute strength approach is not a viable method for the calculation of the Pareto frontier of the Weir Tool. The application of existing genetic algorithm (GA) software, which employs evolutionary principles to 'evolve' optimal solutions was another option that was investigated. Unfortunately the structure of the problem did not fit the requirements of available GA software and it was beyond the scope of the project for a bespoke algorithm to be developed. Instead an approach was taken to randomly generate and plot potential Weir Tool decisions until the boundary of the decision space emerged. As the likelihood of an option on the Pareto frontier being thrown up by chance is inconceivably small, the random generation of decisions was constrained by removing weir modification options that were clearly suboptimal. For instance, the installation of Alaskan A fish passes relative to eel passes were more expensive and less effective. Of the objectives the participants were trying to maximise, only eel benefited from this modification, and so it could be discarded. In this way, for the first exercise where the participants aimed to maximise only two objectives; eel and microhydro, the number of potential combinations of modifications per weir was greatly reduced and M was reduced to seven (shown in Table 6.5). Further simplification was also achieved by excluding many weirs that were high up in the catchment from the random generation of potential decisions as the eel and microhydro models only produced high values when weirs low down in the catchment were modified. This enabled the reduction of W down to 117. Such pruning of tributaries was also done by O'Hanley *et al.* (2005) in their work to optimise the location of dam removals.

Table 6.5. The seven combinations of weir modifications that could potentially be used in decisions that lie on the Pareto frontier for exercise 1, the objectives of which were to maximise habitat accessibility for eel and hydroelectricity production.

Combinations of potential modifications	Effect on eel or microhydro	Total cost (£)
No change	No effect (No eels pass, no hydroelectricity produced)	0
A microhydro installed	Hydroelectricity output increased	275,000
A microhydro installed plus weir height increased to 3m	Hydroelectricity output increased by more than by the installation of a microhydro alone	345,000
A microhydro installed, weir height increased to 3m, plus an eel pass installed	Hydroelectricity output increased by more than by the installation of a microhydro alone and 95% of eel can pass	375,000
A microhydro installed plus an eel pass installed	Hydroelectricity output increased and 95% of eel can pass	305,000
An eel pass installed	95% of eel can pass	30,000
Weir removed	100% of eel can pass, no hydroelectricity can be produced	50,000

But even when M = 7 and W = 117, X is still extremely high at $\sim 10^{99}$, and the chance of randomly generating a random decision that scores highly for both objectives remains exceedingly low. Therefore, the decision was taken to produce 'seed' decisions from which new high scoring decisions could be randomly generated. The seed decisions consisted of the expenditure of some of the budget of exercise 1 on the modification of specific weirs that were known to be essential if high hydroelectricity or eel scores were to be achieved. For example, to maximise the eel objective, it was vital that the most downstream weirs on the main stem of the Don had contiguous modifications to make them passable to eel, and so a seed scenario would have these modifications in place. After the river network begins to branch on the other hand, it is very difficult to know how many weirs up the various tributaries need to have their passability increased to maximise habitat accessibility for eel, and so this is best left to the process of randomly generating decisions to identify.

In total seven seed decisions were used, including two that maximised either eel or microhydro. The other five were designed to generate decisions at various levels of trade off between the eel and hydroelectricity scenarios. For each of the decision seeds, between 1 and 2 million decisions were randomly generated, giving a total of between 7 and 14 million. Because an exhaustive method to identify all potential decisions has not been used, it cannot be assumed that the upper bound of the decision space produced by these decisions match the Pareto frontier. However, it is likely to be in the vicinity of the Pareto frontier, and be approximately parallel. As a consequence it can be used in the same way as a benchmark to measure the effectiveness of decisions made in the experiment. Some inaccuracy in the measure of effectiveness will be caused due to the Pareto frontier not being exactly parallel, but this will only be consequential if the P-value of the statistical comparison of the two groups is close to the threshold determining whether there is a significant difference or not.

The delineation of the Pareto frontier for exercise 2 was beyond the scope of this research as it was infeasible within the timeframe. This is because exercise 2 includes more objectives, adding extra dimensions to the decision space, and also requires the inclusion of all the weirs and many more modifications, meaning that X was greatly increased. The process of calculating the frontier for exercise 1 was already computationally demanding and time consuming, and would become unworkable if the same approach was taken with exercise 2. It is suggested that Genetic Algorithms (GAs) could potentially be used to delineate the Pareto frontier of the decision space in exercise 2, as they can efficiently find solutions in large decision spaces (Haupt & Haupt 2004). However, this would essentially require a new program of research as no prebuilt software was appropriate for the management problem and a bespoke GA to evolve decisions on or close to the Pareto frontier of exercise 2 would need developing.

Such a GA would work by treating each individual weir as a separate gene and all the weirs together as a genome. Each potential set of modifications for a weir (e.g. such as those in Table 6.5) is an allele (gene variants, like genes for blue, brown or green eyes). The process would then start with the generation of a population of genomes and would continue to produce the genetic variation on which evolution can work where each gene (weir) has a small chance of mutating to another allele (modification set). The fitness of each genome could then be assessed by weighting and summing how it performs with regard to the management objectives. The weightings can be set to determine which part of the Pareto frontier has the highest fitness, which consequently gives control of the location on the frontier that the GA will select towards. The proportion of those genomes found to have the highest fitness can then be used to spawn the next generation through the crossbreeding of genomes (i.e. swapping alleles) and random mutation. As the implementation of the GA approach was not feasible over the course of this research only the results of the analysis of exercise 1 are presented.

The decisions the participants made during exercise 1 of the experiment are presented in table 6.6 and plotted with the randomly generated decision space in Figure 6.3. Participants in both the experimental and control group made decisions that vary greatly with regard to their microhydro and eel scores. Both groups produced some decisions that are effective, being close to the upper bound of the decision space, and others that are ineffective, scoring poorly for both objectives. Direct comparison of the microhydro scores reveals that those in the control group produced decisions that had significantly higher microhydro scores (Two sample $t(14)=2.71$, $P < 0.05$). While the mean eel score of the decisions made by the experimental group is higher than that of the control group, there was not a significant difference (Two sample $t(14)=-0.98$, P = n.s.). Three decisions made in the experimental group have notably high eel scores, though the sample size is small and no outliers are detected (Grubbs' test, P = n.s.). For the distance of the decisions from the Pareto frontier, no significant difference was found between the two groups (Kruskal–Wallis test, d.f. =1, P = n.s.). There was however a significant difference between the control and experimental groups in terms of the distributions of the decisions within the decision space, where the eel and microhydro values were treated as dependent variables, and the treatment and control groups independent variables (MANOVA, $p = 0.046$).

Confidence the participant had in the decision they made in exercise 1 is plotted against eel and microhydro scores in Figure 6.4. Confidence correlated with decision effectiveness (Spearman's Rho=0.53, 14 d.f., $P < 0.05$), showing that participants were to some degree able to tell the quality of the decisions they were making.

Table 6.6. The results of exercise 1 where participants had to maximise habitat accessibility for eel and hydroelectricity production. Note, there are fewer participants in table 6.6 than in table 6.2, as a few of the scenarios developed by the participants were lost during the experiment. For example, one participant saved over their scenario created for exercise 1 with the scenario they had created for exercise 2.

	Control group			Experimental group	
Participant	Microhydro score (MWh)	Eel score (proportion from 0.33 -1)	Participant	Microhydro score (MWh)	Eel score (proportion from 0.33 -1)
1	1381	0.45	1	176	0.50
2	2070	0.49	2	563	0.38
3	2272	0.33	3	1479	0.38
4	2377	0.55	4	2381	0.51
5	2443	0.50	5	2176	0.65
6	2416	0.37	6	1449	0.38
7	2784	0.57	7	1592	0.65
			8	1633	0.65
			9	1437	0.57
Mean	2249	0.47		1432	0.52
SD	439	0.09		694	0.12

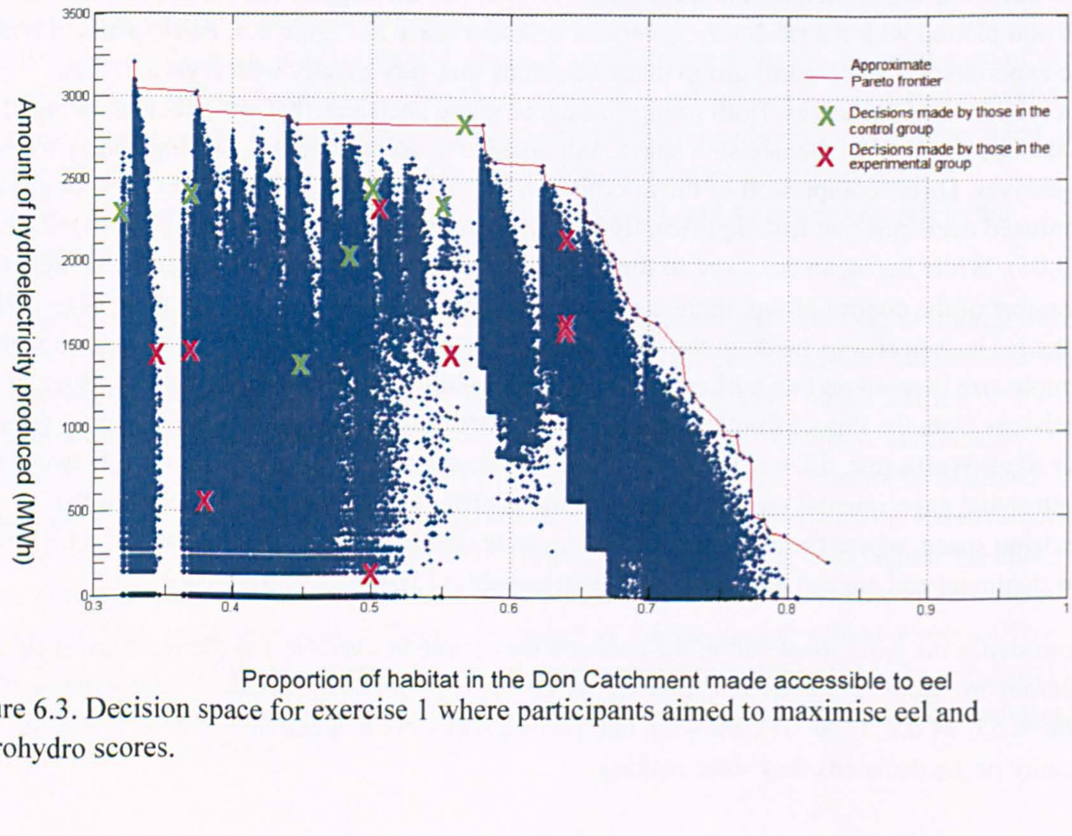


Figure 6.3. Decision space for exercise 1 where participants aimed to maximise eel and microhydro scores.

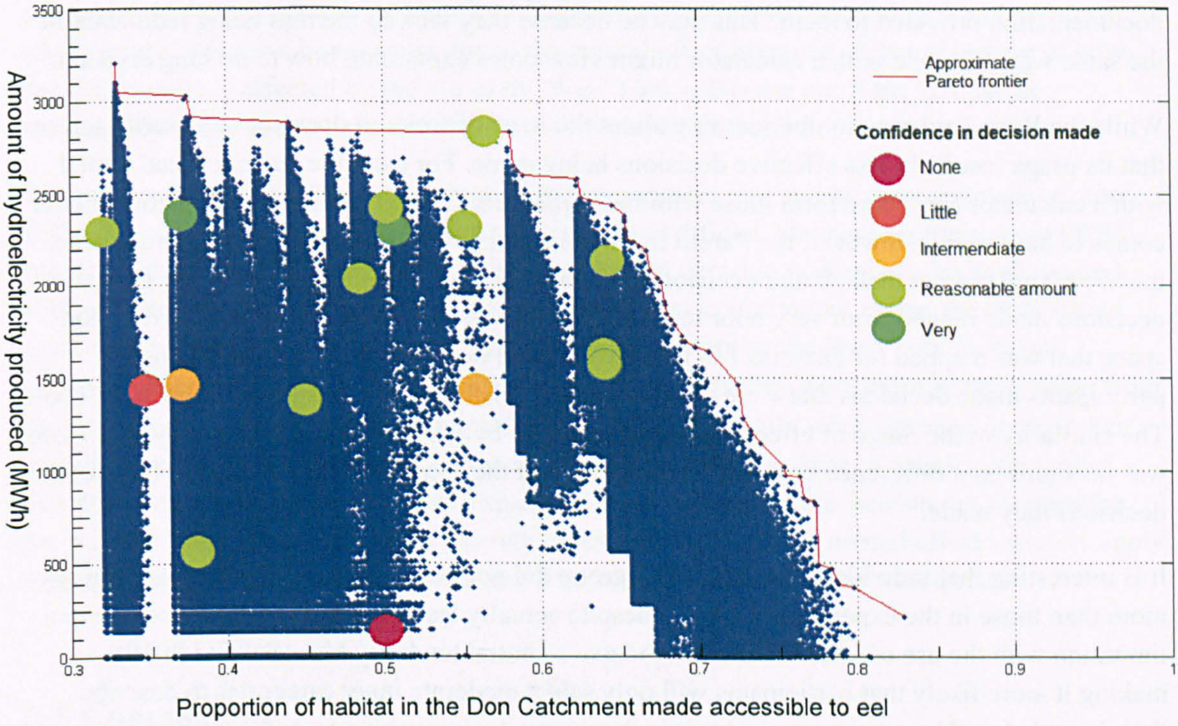


Figure 6.4. Confidence participants had in the decision they made in exercise 1 plotted against eel and microhydro scores.

6.4 Discussion

Contrary to expectations, in the experiment it was found that the group using the DSS to plan catchment intervention strategies learnt significantly less information about the environmental issue of weir impoundment and modification than the control group. There could be many reasons to explain why this occurred. Three possible reasons are that the Weir Tool may be too complex so that users do not fully absorb the information it presents to them, the Weir Tool may be less effective at communicating information, or the Weir Tool was less successful at stimulating learning. As the participants had little trouble using the Weir Tool, and the information it presented to them was no more complex than the information provided in the documentation used by the control group, then the first reason is unlikely. Information was also easy to access using the Weir Tool; the GUI being composed of only two web pages. Information was more conveniently available than in the in the documentation the control group depended on, which had multiple pages. Therefore the second reason is also improbable. Instead, it is suggested that the most likely reason for the results is that the Weir Tool is not effective at stimulating learning. As mentioned earlier, members of the control group were observed to carefully scrutinise the maps and documentation provided with many making extensive notes. They seemed to find the process mentally taxing (hence the sighing) as opposed to the experimental group who used the Weir Tool in a casual manner. The situation could parallel that of the advent of the calculator, which by providing mathematical calculations on demand without the need for mental effort has resulted in a decline in standards of mental arithmetic. It was also noted that the group using the Weir Tool rarely used the maps and other documentation provided to them. This may be because they viewed them as being redundant in the same way someone with a calculator might view notes explaining how to do long division.

While the Weir Tool may inhibit learning about the issue of weirs, it does not necessarily follow that its usage results in less effective decisions being made. For example, an individual armed with a calculator can outperform those with the highest capacity to do mental arithmetic when it comes to hard sums. However, the Pareto frontier analysis of exercise 1 shows that those using the Weir Tool did not make better decisions than those in the control group. For both groups, decisions made ranged from very poor to effective. Indeed, if the upper bound of the decision space that was mapped for exercise 1 is in the vicinity of the Pareto frontier, then some participants made decisions that were close to optimal, with or without the use of the Weir Tool. The similarity in the range of effectiveness of decisions by the two groups is probably why there was no significant difference between them in terms of the confidence participants felt about the decisions they made.

It is interesting that individuals in the control group did not perceive themselves as learning any more than those in the experimental group, despite actually leaning more. This may be due to a limitation with the use of Likert items which have a central tendency bias (Salkind 2010), making it more likely that participants will only select moderate inner categories to describe their knowledge. The consequence of this is that it may be insensitive to differences in perceived knowledge between the two groups. However, an alternative possible explanation for the result is that people are not very sensitive to gauging how much information they have learnt during a decision making process. If this is the case then it has implications for the evaluation of DSSs. Evaluation is sometimes done by interviewing potential users of DSSs such as official decision makers (e.g. Jude *et al.* 2006)), but if the users of a DSS are not aware of how much information they are learning through its use, they will not be able to provide detailed feedback to the interviewer on whether a DSSs has helped them learn. More work research needs to be done to find out whether the perceived knowledge gain result is an artefact of the Likert item, or an actual reflection of how aware humans are of their own learning during decision making. In contrast to perceived knowledge gain, the results show that despite the complexity and uncertainty of developing a weir modification strategy, the confidence participants had in the decisions they made during exercise 1 was weakly correlated with decision effectiveness. This shows that participants were consciously or unconsciously able to tell the quality of the decisions they were making, indicating that it is hypothetically possible that interviews conducted to evaluate a DSS could reveal whether the DSS would lead to more effective decision making.

As the decisions made by the control group and experimental group were found to have significantly different distributions in the decision space, it appears that the usage of the Weir Tool influenced the way decisions were made. Looking at Figure 6.3, it can be seen that decisions made by the control group tended to emphasise microhydro production, whereas those in the experimental group had better eel scores and poorer microhydro scores. The significant difference between the distributions of the decisions was only weak, but if it is not due to chance then it indicates that the aids people use when making decisions can not only potentially improve decision making, but can also influence the way decision makers make tradeoffs between different objectives.

One experiment finding in favour of the Weir Tool is that its users appeared to enjoy themselves during the experiment more than the participants in the control group did. Therefore an advantage of such DSSs may be to make ICM more appealing and get stakeholders involved whom might otherwise be reluctant due to the mental effort involved. A better picture of how decision quality is affected by the use of the Weir Tool will come out if the GA can be successfully employed to delineate the Pareto frontier of exercise 2.

It must be acknowledged that the results of this experiment may not be representative of other DSSs. The experimental conditions are contrived and artificial, there are multiple ways DSSs can be produced and there are many diverse ways ICM decision making can be implemented, with or without a DSS. For example, the experiment was conservative in that the participants used were not experts and therefore might be less able to utilise the Weir Tool to its full potential. The reverse also applies; that by not being experts they were more likely to learn from the Weir Tool. In addition, the participants worked independently when drawing up their weir modification strategies in contrast to how ICM is supposed to be done; a collaborative effort that draws on a wide range of pooled expertise. Nevertheless, the mechanism put forward for the way the Weir Tool might lower the rate of learning by reducing mental effort logically apply to the usage of DSSs in most contexts, and if correct, must therefore be widespread.

6.5 Conclusions

The experiment ran found that the use of the Weir Tool resulted in less knowledge being gained by its users relative to those using more conventional map and rule based approaches to catchment management decision making. It is suggested that this may be a widespread effect resulting from less mental effort being required of the users of DSSs as compared to those using more basic tools to aid decision making. This has implications for the design and utilisation of DSSs, especially as one of the proposed advantages of such systems is to facilitate learning (Westmacott 2001; Walker 2002).

The results of the experiment also demonstrate that there may not be a correspondence between how much people believe they have learnt during the decision making process and how much they have actually learnt. In contrast, decision makers appear to be aware when their decisions are more effective. These findings must be considered by those planning to use interviews to evaluate DSSs.

The experimental design looks for evidence of different aspects of decision making quality, and consequently will provide a relatively robust way of assessing whether an approach to deliver ICM improves decision quality. The unexpected initial findings show that it should not be assumed that after usability, trust and institutional barriers to the uptake of DSSs are resolved, the use of a DSS will lead to improved decision making in all its aspects. More evidence must be gathered to understand the advantages and disadvantages of DSSs, so that their potential can be fully utilised.

7 Synthesis

7.1 Research context

If we as a society are to develop the capacity to implement a holistic approach to environmental management then progress must be made in research disciplines that span engineering, the sciences and the humanities. It is by necessity an interdisciplinary research area. Because catchment interventions such as weir modification affect a variety of human interests, research is also driven and affected by a variety of different policies and stakeholder movements. The wider context of the work presented in this thesis is described below in terms of research, and relevant policy and stakeholder groups.

The ecological impacts of impoundments such as weirs have received growing interest in the last couple of decades. One reason is because there is a growing trend for people to put intrinsic value on the health of river ecosystems (Findlay & Taylor 2006), and dams are increasingly being perceived as structures that degrade river ecosystems (Stanley *et al.* 2002). In some countries such as in the US, dam removal has become popular, and has vocal groups who lobby in its favour (Stanley & Doyle 2002).

Comparative to large dams, weirs have received little attention. Large dams have been the focus of more studies because of their greater and more obvious effect on river ecosystems. Detailed ecological data has been collected to show their effect on specific groups of organisms (e.g. Xu *et al.* 2011) and comprehensive reviews of their effects on the entire ecosystem have been published (e.g. Baxter 1977).

However, for a number of reasons things are now changing. The river restoration and the river trust movements in the UK are keenly aware of the negative impacts impoundments can have on river ecosystems and are interested in weir modification as a tools with which the ecosystems of rivers can be enhanced (e.g. The River Restoration Centre 2002). At the same time, the rising demand for renewable energy has encouraged community groups (Sheffield Renewables 2008) and institutions (Environment Agency 2010b) to investigate the hydroelectricity that can be generated by microhydro schemes installed on weirs.

The rise of the ES concept is also focussing attention on the impact human activities such as weir impoundment have on river ecosystems. Its promise as a useful way to assess potential river interventions is recognised in the literature (Brismar 2002; Everard & Moggridge 2011) and the approach has been received positively by some governmental organisations in the UK including the Department for Environment, Food and Rural Affairs (Defra 2007b). As a result organisations ranging from community groups to governmental departments have become more conscious of the utilitarian benefits river ecosystems provide. Consequently they are beginning to ask how the potential interventions they wish to implement will affect the ESs rivers provide to society.

Implicitly recognising the utilitarian value rivers provide is the Water Framework Directive (WFD) legislation, which legally obliges the UK to achieve 'Good Ecological Status' i.e.

has been greater awareness that variation in impoundment size, type and function is significant in determining the effect it has on the river ecosystem (Poff and Hart 2002). While in the past most research focussed on the largest impoundment, weirs are now recognised as deserving as much attention, and a variety of studies have investigated their ecological impact on river ecosystems (e.g. Pohlon *et al.* 2007, Mueller *et al.* 2011). The review of these studies in chapter 1 is the first of its kind and shows that just like large impoundments weirs can strongly influence the river ecosystem and a wide range of riverine biota. Just how numerous weirs are across the world is unknown, but the limited amount of data collated in chapter 1 on abundances in different regions suggests that weirs occur in very large numbers across the globe.

In chapter 2 a holistic evaluatory framework is put together using river ESs with which alternative weir modification scenarios can be assessed. Meyer (1997) was amongst the first to argue that river ESs should be used as a holistic framework with which to assess alternative river management interventions, and identified a typology of ESs for this purpose. A number of other studies have since been published proposing their own typologies. Strange *et al.* (1999) assembled a set of river ESs and reviewed the ecology and hydrology of the South Platte River to understand how this related to ES provision. Brismar (2002) again assembled a typology of river ESs and then reviewed how the construction of large dams impacted on provision. A few studies have gone on to apply these typologies to case studies. For example Everard and Moggridge (2011) and Loomis *et al.* (2000) used a variety of approaches to place monetary values on river ESs. As the published typologies of river ESs mix end welfare benefits to humans with underlying supporting ecosystem processes, a new typology is adapted that is more suitable for use as a framework to evaluate weir modification options. The review of how weirs affect the ESs in this typology is a first, and serves to illustrate how complicated and context dependent the impact of weirs is on ES provision.

Of the ESs identified in chapter 2, one important group are the sociocultural ESs. Remarkably, of 254 criteria based on ES provision used to assess the success of various ecological restoration projects identified by Rey Benayas *et al.* (2009), none were of sociocultural ESs. This reflects their subjective and qualitative nature (Natural England 2011), making it difficult to predict how they will change after management interventions have been implemented. The neglect of sociocultural ESs is a recognised problem (Daniel *et al.* 2012), and it is argued in the literature that more needs to be done to consider them in decision making (Schaich *et al.* 2010, Daniel *et al.* 2012). Outside of the ES literature, other disciplines have struggled with the prediction of sociocultural ESs under different disciplinary names, and have developed a number of basic approaches to deal with them. To account for the cultural significance Maori place on river ecosystems in New Zealand, Tipa and Teirney (2003) developed a cultural health index that allowed the cultural value of a river be ascribed using rules set by Maori in interviews. In the field of landscape aesthetics, visualisation approaches have been used to collect data on the preferences of observers across a landscape variable with which statistical models can be built (Daniel 2001). For example, in such a manner Silvennoinen *et al.* (2001) created a regression that predicted the aesthetic quality of stands of trees based on variables such as the composition of species and tree height.

There are a number of limitations with these approaches. Firstly indices and regressions do not easily represent uncertainty with which variation in the perception of the holders of sociocultural values can be captured and communicated. Secondly unfeasibly large amounts of data need to be collected when multiple variables are needed in multiple regressions or rule based indices. Chapter 3 addresses the need for a better approach that allows sociocultural ESs slightly different from pristine ecological condition (EC 2000). It does this because it assumes that a good ecological state will provide more benefits to society than a degraded ecosystem. Weir modification is one of the measures that are expected to contribute to the UK meeting its WFD targets (Environment Agency 2009).

Therefore there are many reasons why there is increasing interest on the impacts weirs have on river ecosystems, and how weir modification decision making can be conducted. More studies are now being directed at weirs. For example, the recently published study by Mueller *et al.* (2011) compares how the different conditions upstream and downstream of weirs affect the ecological communities that are found there. Several PhD students have been funded at the universities of Sheffield and Hull to look at the ecological impacts of microhydro schemes attached to weirs. It is in this context that this research was conducted.

7.2 What has been achieved by this research?

Weirs are numerous, widespread and can have a profound effect on river ecosystems. As they affect a wide range of stakeholder interests, and multiple weirs can interact in a complicated fashion, they must be managed using holistic principles advocated by Integrated Catchment Management (ICM). For effective and fair weir modification decisions to be made, all stakeholder interests must be used to evaluate alternative weir modification options. So that decision makers can make the most of the synergies that can occur between interventions, and avoid the conflicts, they need to know how multiple weir modifications interact. To follow these principles, decision makers must account for a huge amount of information and use it to find effective decisions. The objective of the research presented in this thesis is to apply these principles to the management of weirs in the Don Catchment. Specifically, a holistic framework of criteria that could be used to evaluate alternative weir modification options was assembled. The challenge of predicting the effect of weir modifications on sociocultural ecosystem services (ESs) was tackled, and a modelling approach that accounted for the interdependent effects spatially separated weir modifications have on catchment connectivity was developed. This enabled the construction of a prototype web-based DSS dubbed the Weir Tool that allows decision makers to manage the information that the models produce to plan weir modification at the catchment scale. The finished Weir Tool was used in a controlled experiment to test the basic assumption that the usage of such DSSs is required to improve decision making.

The thesis begins with a review of the effects weirs have on river ecosystems. As was briefly touched upon above, the effect of large impoundments on river ecosystems has long been a focus of study. Indeed Baxter produced a comprehensive review in 1977. Since this review was published our understanding of the impacts of river impoundment has increased significantly, with many studies answering ever more specific questions. For example, Blinn and Cole (1991) and Quist *et al.* (2005) studied the changes to the invertebrate and fish communities occurring after the construction of large dams, and Kimmel and Groeger (1983) reviewed how impounded ecosystems changed over time. In the last few decades a surge in academic interest in the ecological impacts of impoundments has been brought about due to the rise of the dam removal movement. Multiple studies have collected ecological data pre- and post- dam removal to document what changes occur in the river ecosystem (e.g. Stanley *et al.* 2002, Sethi *et al.* 2004). The ecological impacts of impoundments and the changes occurring after impoundments are removed have been reviewed by Bednarek (2001) and Hart *et al.* (2002). More recently there has been greater awareness that variation in impoundment size, type and function is significant in determining the effect it has on the river ecosystem (Poff and Hart 2002). While in the past most research focussed on the largest impoundment, weirs are now recognised as deserving as much attention, and a variety of studies have investigated their ecological impact on river ecosystems (e.g. Pohlon *et al.* 2007, Mueller *et al.* 2011). The review of these studies in chapter 1 is the first of its kind and shows that just like large impoundments weirs can strongly influence the river ecosystem and a wide range of riverine biota. Just how numerous weirs are across the world is unknown, but the limited amount of data collated in chapter 1 on abundances in different regions suggests that weirs occur in very large numbers across the globe.

In chapter 2 a holistic evaluatory framework is put together using river ESs with which alternative weir modification scenarios can be assessed. Meyer (1997) was amongst the first to argue that river ESs should be used as a holistic framework with which to assess alternative river management interventions, and identified a typology of ESs for this purpose. A number of other studies have since been published proposing their own typologies. Strange *et al.* (1999) assembled a set of river ESs and reviewed the ecology and hydrology of the South Platte River to understand how this related to ES provision. Brismar (2002) again assembled a typology of river ESs and then reviewed how the construction of large dams impacted on provision. A few studies have gone on to apply these typologies to case studies. For example Everard and Moggridge (2011) and Loomis *et al.* (2000) used a variety of approaches to place monetary values on river ESs. As the published typologies of river ESs mix end welfare benefits to humans with underlying supporting ecosystem processes, a new typology is adapted that is more suitable for use as a framework to evaluate weir modification options. The review of how weirs affect the ESs in this typology is a first, and serves to illustrate how complicated and context dependent the impact of weirs is on ES provision.

Of the ESs identified in chapter 2, one important group are the sociocultural ESs. Remarkably, of 254 criteria based on ES provision used to assess the success of various ecological restoration projects identified by Rey Benayas *et al.* (2009), none were of sociocultural ESs. This reflects their subjective and qualitative nature (Natural England 2011), making it difficult to predict how they will change after management interventions have been implemented. The neglect of sociocultural ESs is a recognised problem (Daniel *et al.* 2012), and it is argued in the literature that more needs to be done to consider them in decision making (Schaich *et al.* 2010, Daniel *et al.* 2012). Outside of the ES literature, other disciplines have struggled with the prediction of sociocultural ESs under different disciplinary names, and have developed a number of basic approaches to deal with them. To account for the cultural significance Maori place on river ecosystems in New Zealand, Tipa and Teirney (2003) developed a cultural health index that allowed the cultural value of a river be ascribed using rules set by Maori in interviews. In the field of landscape aesthetics, visualisation approaches have been used to collect data on the preferences of observers across a landscape variable with which statistical models can be built (Daniel 2001). For example, in such a manner Silvennoinen *et al.* (2001) created a regression that predicted the aesthetic quality of stands of trees based on variables such as the composition of species and tree height.

There are a number of limitations with these approaches. Firstly indices and regressions do not easily represent uncertainty with which variation in the perception of the holders of sociocultural values can be captured and communicated. Secondly unfeasibly large amounts of data need to be collected when multiple variables are needed in multiple regressions or rule based indices. Chapter 3 addresses the need for a better approach that allows sociocultural ESs to be predicted to support the application of the ES concept to environmental management. Bayesian Networks (BNs) are identified as a solution because they use probabilities to describe the relationships between variables. This allows people who hold sociocultural values to describe cause-effect relationships between the variables that predict them, even if the mechanisms by which the dependent and independent variables interact are not known. As a consequence, uncertainty can be captured, and the collection of empirical data may not be necessary.

The BN approach is applied to a sociocultural ES affected by weirs and weir modification in the Don Catchment, that of canoeing. Weirs can pose a danger to canoeists, but chuting weirs is something that canoeists also find fun. A BN was built using expert knowledge provided by canoeists to predict how weir modification affected weir danger and weir fun. The process of model construction was found to be relatively intuitive for the canoeists, with the exception of the probability elicitation stage, which was offputtingly long and abstract. It is concluded that despite a number of caveats, BNs offer a potentially important method for allowing sociocultural ESs to be considered in ICM. It was not possible to find any ES literature that dealt with the problem of modelling of sociocultural ESs, and so chapter 3, is perhaps the first to suggest that the characteristics of BNs makes them particularly suited for the modelling of sociocultural ESs.

Another barrier to the implementation of ICM is the potentially complex interactions that can occur between different weirs when multiple weir modifications are implemented. In chapter 4 we develop a spatially explicit modelling approach to account for the interdependent effects modifications have on river connectivity for the European eel (*Anguilla anguilla*), Atlantic salmon (*Salmo salar*), signal crayfish (*Pacifastacus leniusculus*) and white-clawed crayfish (*Austropotamobius pallipes*). Weir modifications that improve river connectivity are one major set of measures that are anticipated will help the UK to achieve its WFD targets (Environment Agency 2009). Modifications must be chosen carefully, as they are very costly and so the limited number that can be afforded can be placed in locations work synergistically. Kemp and O'Hanley (2010) review different methods that can be taken to prioritise barriers for connectivity improvements, and stress that because scoring-and-ranking approaches do not consider the interactions between multiple weirs in a catchment, they can recommend inefficient solutions.

Instead the modelling approach taken in chapter 4 is spatially explicit, allowing the interplay between multiple weir modifications to be accounted for. It is not unique in this respect, a number of other studies have also considered the interaction between multiple barriers (e.g. Kuby *et al.* 2005; O'Hanley & Tomberlin 2005). The model does however differ from these in that it incorporates expert or model derived weightings of habitat quality into the modelling. To increase the usefulness of the models for salmon and eel, two alternative methods were used to discriminate between different levels of habitat quality in the Don Catchment. Because of the lack of published information on the habitat requirements of eel (a situation typical of most species), expert judgement was used to estimate how several variables determined habitat quality for this species. For salmon, which has been studied more extensively, a hydrological model was used to map those areas where flow conditions are within the range of what this species has been observed to utilise as spawning or as rearing habitat. The model enables the real time comparison of alternative weir modification options, so that the consequences of changes in connectivity for different organisms can be understood. To demonstrate this several weir modification scenarios were designed for the Don Catchment, targeting different parts.

Because the approach allows the exploration of different weir modification options in real time, it is suited to the messy and iterative process of ICM decision making. The model was used to investigate the cumulative impact partially passable barriers had on migrating fish using the Don Catchment as an example. While concerns about the cumulative effect of multiple barriers has been raised in the literature (e.g. Kemp and O'Hanley 2010), the work presented in chapter 4 is the first to demonstrate just how significant it is, even when fish passes are highly effective.

The Weir Tool was built to bring together the different models, so they could be used more efficiently, and the results could be easily communicated in a manageable way to the user. The Weir Tool lets the user plan weir modification scenarios that are then evaluated using the outputs of the models. Its construction is described in chapter 5. It consists of a web-based graphical user interface (GUI) that displays the weirs and the rivers in the Don Catchment overlaid on a Google Map. Also presented within the GUI is a rose diagram in which the outputs of the canoeing BN, the river connectivity models, and a hydroelectricity model are displayed. The user can specify multiple weir modifications in the GUI, and then receive feedback from the models permitting the user to assess the performance of the weir modification strategy they have entered.

A fundamental part of ICM, as with all environmental management, is the making of decisions. The decision maker wishes to find those management interventions that will provide the most positive outcomes. Often decision makers face a vast number of alternative decisions, and need to consider numerous criteria. Due to the complexity of environmental management, DSSs are believed by some to be essential for its successful implementation (Matthies *et al.* 2007). It is generally assumed that if they are employed, improved decision making will result. Chapter 6 presents the results of an experiment to test this assumption.

The first step in designing the experiment was to identify measures of decision quality that could be recorded in an experimental setting. This enabled an experiment to be run in which one group employed the Weir Tool to make hypothetical weir modification decisions, whereas the control group used a conventional map and rule based approach. In contrast to expectations, users of the Weir Tool learnt less about the environmental issue of weir modification compared to the control group, and did not make more effective decisions.

The running of experiments with the objective of testing whether a DSS improves decision making is not unique to this study. Indeed George *et al.* (1990) ran an experiment to test whether a DSS helped groups reach a consensus in a collaborative setting. However, in the context of the development of DSSs to aid environmental management, an assessment of their usefulness is rarely presented in the literature. If one is, it is usually done in a qualitative sense by interviewing potential users to see how they feel about the DSS (e.g Jude *et al.* 2006; Holzkämper, *et al.* 2012). The author was unable to find any cases where a DSS produced to aid environmental management had been assessed in a quantitative sense. The results of the experiment to test whether the Weir Tool improves decision making demonstrate the importance of assessing the utility of DSSs in a quantitative sense as well as conducting qualitative interviews.

7.3 Wider implications of the research

There is evidence that weirs affect the wide variety of organisms that inhabit river ecosystems, as well as a range of ESs provided by rivers. Therefore decision makers dealing with weirs must be aware of the wide range of potential impacts weir modification can have. But the impact of weirs is context specific, dependent on economic, environmental and social factors, meaning generalisations cannot be made. This makes rigid policy stances towards weirs inappropriate. Instead decision makers need to consider weirs on a case by case basis, while maintaining a catchment overview so that they keep in mind the interactions multiple weirs can have. Careful consideration must be given to how different ESs will be traded off when weirs are modified, as well as to the question of whether modification will help a river stretch achieve its WFD targets.

BNs offer a modelling approach by which sociocultural ESs can be predicted. Conditional probabilities can be used to successfully describe the relationships between subjective and qualitative variables. Experts generally found the process of BN construction engaging, but the use of questionnaires to elicit probabilities can be a tiresome exercise due to their length and abstract nature. This issue can be avoided by limiting the number of cause-effect pathways and number of variable states in a BN, though this may in turn trade off some of the usefulness of the model. The structure of the cause effect network is important to the predictive accuracy of a BN. Long chains of nodes and variables with few states can magnify uncertainty, resulting in model outputs that are more insensitive to model inputs than they should be. Efforts should be made during the construction if BNs to avoid these structural features.

Spatial models that factor in the hierarchy of weirs within a river network can account for the interactions multiple weir modifications implemented to improve river connectivity can have. The model presented in chapter 4 can be used to explore how multiple weir modifications affects access to habitat, allowing the comparison of how alternative strategies to open up catchments affect various species. For example, in the scenarios examined in chapter 4, it was found that different strategies benefited certain species over others, signifying that deciding on what connectivity improvements to implement involves making tradeoffs between various species.

Another finding was that the output of the model was very sensitive to how passable weirs became after fish passes were installed. Slight changes to fish pass efficiency produce very different results. The implications for those prioritising barriers for connectivity enhancements is that the cumulative effect of a series of fish passes can quickly whittle down a population of migrating fish, even when passes are highly efficient. When there is potential for anadromous fish like salmon to recolonise a river, it could well be more effectual to actively stock fish if multiple fish passes must be ascended for suitable spawning habitat to be reached. Otherwise, the cumulative effect of the weirs can greatly reduce the chances of enough salmon reaching the spawning grounds to naturally re-establish a population.

The results of the experiment to test whether the Weir Tool improved decision making has major implications to the use of DSSs in ICM. The results suggest that it cannot be assumed that the usage of a DSS will automatically lead to improved decision making. If models like the canoeing BN and the river connectivity models presented in this thesis are integrated into a DSS, careful consideration must be put into how the DSS will function and how it will be used. The experiment provides an alarming example of how an easy to use DSS that in the experimental setting was perfectly accurate (as the same models that compose it are used again to generate the Pareto frontier that is used to measure decision effectiveness) did not lead to improved decision making compared to a control group. By reducing the amount of mental effort needed to make decisions, it may be that some DSSs actually inhibit learning. On the other hand, this may be the reason why those using the Weir Tool in the experiment seemed to enjoy themselves more than those in the control group. These findings raise questions on how DSSs should be used, and what benefits we can expect them to provide.

The experiment also has implications for the assessment of DSSs. The results indicate that users of a DSS may not be clearly aware of how much information they are learning through its usage, and so they cannot be relied upon to report how helpful a DSS has been in teaching them information about the decision problem. In contrast, the confidence experiment had in the decisions they made did correlate with decision effectiveness. If this holds true more widely, it may be that decision confidence can be measured as an indicator with which to assess the helpfulness of a DSS.

7.4 Questions raised by the research

During the course of this research, numerous gaps in our understanding have become apparent. Below some of these key questions are discussed.

While increasing amounts of data are being gathered on the ecological impacts of weirs, some components of freshwater ecosystems have been neglected. Freshwater fungi for example are an important group with the essential function in freshwater ecosystems of decomposing celluloses and lignocelluloses in detritus (Wong *et al.* 1998). No work has been done to see if weirs affect this group and consequently the capacity of rivers to cycle nutrients. In addition, the exposed riverine sediments that form downstream of weirs (e.g. see Figure 7.1) form a valuable type of habitat well known for its unique community of riparian arthropods. Due to the decline of this habitat type because of river modification (Tockner *et al.* 2003), many of the species of associated invertebrate are rare (Sadler, Bell, & Fowles 2004). The role of weir islands in conserving these species has not been studied.

Figure 7.1. Exposed riverine sediments downstream of a weir in the Don Catchment.
Source: Image taken by Dr Cheryl Gibson and was previously on web-based image hosting service Flickr.

As was discussed in chapter 2, the weir pond itself may provide another type of habitat that are now uncommon in heavily modified rivers, formerly produced by beaver dams, log jams and bank collapses (Hart *et al.* 2002). Therefore it is plausible that in circumstances where weirs increase habitat heterogeneity in rivers, weirs may actually increase biodiversity. Whether this is the case, its implications for river restoration and the efforts to achieve WFD targets needs investigation. In addition, if weir modification is to become an even more important river restoration and WFD measure, tools will be needed to predict how weir modification will alter river communities.

One research priority in the application of the ES concept to weir modification, or to any environmental management issue, is the development of approaches to identify and categorise the numerous sociocultural values people place in river ecosystems. When the whole world can hold sociocultural values that are provided by an ecosystem, how can the decision maker find a practical and equitable method to select a representative subset to consider in the decision making process?

A problem that is perhaps even more difficult to resolve is the need to estimate how important ESs are that feed into economic processes. The human welfare benefits provided by some ESs that provide economic benefits, such as the production of hydroelectricity are masked by the complexity and diversity of economic processes. It is therefore hard for environmental managers to know how much weight to put on these ESs in the decision making process if they do not know how significant they are for human welfare.

The review of ESs presented in chapter 2 only includes those provisioned by the river in which the weir is sited. But the implementation of the ES framework in weir management decision making needs to be comprehensive, and include those that arise from water bodies that exist because of weirs, such as mill ponds, canals, and irrigation networks. This necessitates that the framework be expanded to include those ESs.

Regarding the use of the BN to model sociocultural ESs, it may be relatively easy to overcome the apparent problem of stakeholder disengagement encountered during the probability elicitation stage. It is suggested that computer visualisation techniques could be used to communicate variables such as weir height instead of via text in a paper based questionnaire. By speeding up communication, this could make probability elicitation more efficient, and by removing the potentially taxing process of mentally visualising variables in hypothetical states, it could make the process more enjoyable. Post BN construction, computer visualisation may also make interaction with the BN more intuitive. How much benefit arises from the use of computer visualisations needs to be investigated. For example, questions that need answering include whether the use of computer visualisations can make probability elicitation more accurate, faster, or more engaging?

A question with relevance to how transferable BNs that predict sociocultural ESs are is how universal are the sociocultural values that people place on ecosystems? Do they vary with attributes such as age, gender, cultural and environmental conditioning etc? If people are repeatedly found to hold a common set, then these can be reapplied as assessment criteria across multiple catchments. Additionally, it would provide insight into the number of people that are required to provide a reflective sample during the probability elicitation stage. If perceptions of value are found to be variable, more people will need to be included in the probability elicitation stage than if they are found to be consistent.

Much research can be done to improve the connectivity models described in chapter 4. One of the most pressing questions raised is exactly how efficient are fish passes? Changes in efficiency of less than 10% can have major implications for the feasibility of strategies to open up river catchments due to the cumulative effect of multiple fish passes. Expert opinion is almost certainly not going to provide the required accuracy. Only large amounts of field data are going to be adequate to work out the efficiencies of the variety of types of fish pass for different species of fish.

Significant improvements to the connectivity models can also be achieved through the improvement of our ability to differentiate between the various levels of habitat quality for riverine species. The less information included in the model on habitat quality, the greater the uncertainty in its output on the benefits of opening up one section of a catchment as compared to another. However knowledge of the habitat requirements of many species is poor (Bond & Lake 2003). More research needs to be done to gain a better understanding of what physicochemical conditions are required by an organism, as well how its interactions with other species (e.g. predators, prey, competitors etc) also determines the quality of habitat.

The lack of information on what determined the quality of habitat for European eel was why expert judgement was used to provide an estimate of habitat suitability for this species. Expert opinion is commonly used in ICM modelling, due to a large number of unknowns that arise from dealing with a wide variety of complex systems, and a lack of resources to gather data (Borowski & Hare 2007; Holzkämper, *et al.* 2012). It is therefore very important that we know how to utilise expert knowledge in catchment management correctly. How expert judgment varies across experts, and the issue of how many experts are required to provide an accurate estimate for use in modelling has been investigated by Czembor *et al*,. (2011), but many other questions remain. For example, how accurate are expert estimates for different types of system? Is there a correlation between how accurate experts perceive themselves to be verses how accurate they actually are? What methods of knowledge elicitation retrieve the most accurate information?

One of the more surprising results presented in this thesis is that in the experimental setting the Weir Tool DSS inhibited learning and its usage did not improve decision making. As DSSs are commonly built in the belief that they can help teach the user and result in better decisions being made, a research priority is therefore to see if the results are replicated for other DSSs. This will help answer the question of how widespread are the effects found in the experiment? For instance, do DSSs consistently inhibit learning, and fail to improve decision making? The factors that determine these effects must be identified so that they can be designed out of DSSs and decision making processes.

7.5 Transferability of methods

The Weir Tool was built to aid weir modification decision making in the Don Catchment in the north of England. This catchment is similar in term of its geology, climate, relief and land use patterns to many others in the UK, though the approaches utilised in this research can be applied to any river catchment as long as the necessary data is available.

In some circumstances it may be possible to use the canoeing BN in other catchments without revision. It contains no spatial information specific to the Don Catchment, and its variables are generic making them relevant elsewhere. Some changes to the model might be necessary if the receiving catchment has novel variables or variable states that need to be considered in the model. For example, there might be a greater range of weir heights in the new catchment, and so a new state may be added to the BN to cover the greater range. If so then it would be necessary for new probabilities to be elicited for those subnetworks in which the variable weir height features as a parent or child node. If changes are made to several well connected nodes (even if these are minor, like a change in state definition), then this can mean that the majority of the probability elicitation process will need to be redone; a very time consuming process.

But it is only valid to reapply a BN that models a sociocultural ES if there is reason to believe the stakeholders in the new catchment will hold the same opinions as the old catchment, and that if the probability elicitation process was redone a similar result would be found. And even if this was the case, it still might be beneficial to reconstruct the BN because the process of involving stakeholders in the construction of a model could well be an important mechanism through which stakeholders build trust in the output of the model (Henriksen *et al.* 2007).

In contrast, the connectivity models require more revision before they can be transferred to another river catchment. The basic concepts, methods and algorithms are transferable, but parameterised into these models is much spatial information, including the structure of the river network, and within this the location of the barriers and (if applicable) focus species. Other spatially explicit data such as water quality can also be used to weight river reaches to produce an indication of habitat quality. For example, in the case of the hydrological modelling done to map potential habitat for salmon, hundreds of river cross sections were used.

Once set up, one advantage of the connectivity models is that they can be expanded relatively easily to include additional species. How challenging this is depends on how sophisticated attempts are to weight habitat quality for these species, and to factor in how porous different types of barrier are. Obviously it also makes sense to include within the model connectivity enhancements to other types of barrier, such as pumping stations or culverts in the model, as well as potential habitat enhancements.

The architecture of the Weir Tool itself makes the system relatively convenient to transfer to other catchments. Its construction is modular so that one model of one catchment can be swapped for a model of another and the database of weir data can be replaced. However, there is some catchment specific information hard coded into the Weir Tool that would need changing, for example, the geographic extent of the Google Map in the GUI. While the net amount of effort required to change the code is small, identifying exactly what needs changing and where could be time consuming.

7.6 Summary of main conclusions

- The impact of weir impoundment on river ecosystems was reviewed, revealing that the effects of weirs can be profound. As the impact varies depending on the environmental, social and economic context it cannot be generalised.
- An evaluatory framework of those ESs affected by weir impoundment was assembled. Again it was found that generalisations could not be made as the effect of weirs on these ESs varied depending on context.
- It was established that BNs are suitable for the modelling of sociocultural ESs, though a major limitation with the approach is the demanding nature of the probability elicitation stage on those providing expert knowledge.
- The interaction between interventions is very important in determining the output of connectivity models, in particular the cumulative effect of fish passes.
- There is a lack of information on the efficiency of fish passes, knowledge of which crucial if it is to be predicted how successful a strategy to open up a river catchment to migratory fish will likely be.
- Models of ESs were integrated into a web-based DSS dubbed the Weir Tool.
- In an experimental setting, users of the Weir Tool learnt less information and made decisions with a similar effectiveness to those in the control.

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Appendices

Appendix a. Construction of the microhydro and weir costing models

The construction of the models to predict the hydropower potential of weirs and report the costs of weir modifications is reported in this appendix.

The microhydro model

Weirs can be exploited to generate a small amount of electricity by channelling the head of water they create through a turbine. Such low-capacity hydroelectricity schemes are known as microhydro. The turbine and its frame can be attached directly onto a weir or placed within a goit. The high abundance of weirs in the UK and the global need to reduce carbon emissions means there is considerable interest nationally in the contribution microhydro technology could make to the national output of renewable energy. An Environment Agency (EA) funded study found that after excluding sites in areas that are particularly environmentally sensitive, there are 4190 locations (the majority weirs) across England and Wales that potentially could provide a relatively high output of hydroelectricity (Environment Agency 2010b). Together, 0.5% of the UK's 2020 energy needs could be met if microhydro were installed at these sites, though the report points out that in reality practical constraints such as proximity to the electricity distribution network means that the true figure is much lower (Environment Agency 2010b). Within the Don Catchment, microhydro schemes are being planned by Sheffield Renewables, a social enterprise, and British Waterways, a public corporation with some waterway maintenance duties. Schemes being investigated are mainly of an Archimedes screw type; the turbine being composed of a helical ridge wrapped around a cylinder that is free to rotate within a tube (see Figure 8.1). The advantages of this type of scheme are that they are relatively efficient over a wide range of flow volumes, and that fish passing through the turbine are not killed (Ritz-Atro 2010).

Figure 8.1 An Archimedes screw type microhydro scheme on the River Monnow, Wales. *Source*: http://www.geograph.org.uk/photo/1538784

Not all weirs have the same potential to generate hydropower. Generally, the higher the head and flow of water at a weir, the greater the quantity of hydroelectricity that can be generated. This is reflected in the formula used to predict the instantaneous output P_i (MW) of a hydropower scheme (British Hydropower Association 2005):

$$P_i = g\mu QH \qquad (8.1)$$

where g = acceleration due to gravity (10m/s^2), μ = efficiency of the hydro scheme, Q = flow passing through the turbine (m^3/s), and H = effective head of water across the turbine (m).

As the output is dependent on river flow which varies greatly across a year, then it is more useful for decision makers to know the annual power output of a hydroelectric scheme. To calculate this, the annual flow exceedance curve of a river can be divided into durations and eq. 1 applied to each. For the model, an approach outlined by Sheffield Renewables (2008) was used that divides the flow exceedance curve into twenty equal parts; Q5, Q10, Q15 ... to Q100 where Q_n is the flow exceeded n % of time. Eq 8.2 is applied, so that:

$$P_{an} = tg * \sum_{1}^{n} \mu_n (Q_n - Q_{95}) H_n \qquad (8.2)$$

where P_{an}= the annual power output (MWh), t = hours in a year (8760),), g=acceleration due to gravity (9.8m/s^2), μ_n is the efficiency for flow Q_n and H_n is the head across the turbine at flow Q_n. The efficiency of the hydro scheme μ_n is a product of turbine efficiency μ_t and electricity generator efficiency μ_g. μ_t and varies with flow. The efficiencies published by Ritz-Atro, a manufacturer of Archimedes screw microhydro schemes, are used (Ritz-Atro 2010). A value of 0.85 is taken from the Sheffield Renewables report (2008) for μ_g, a figure that is approximately constant across flow.

Q_n is the max flow for each portion of the flow exceedance from which the Q95 (river flow that is exceeded 95% of the time through the year) is subtracted as this is required to maintain flow over the weir for environmental reasons. The maximum value $Q_n - Q_{95}$ can be is capped at the maximum capacity of the Archimedes microhydro scheme Sheffield Renewables are interested in installing on the River Don (5 m^3/s).

Effective head of water across the turbine (H_n) is also flow dependent, being greatest under low flow conditions and lowest under high flow conditions when the weir is 'drowned out'. This is captured using an experimentally derived parameter (H_{factor}) that lies between 13 and 27 depending on the physical dimensions of a weir (Sheffield Renewables 2008). An intermediate value of 20 was taken as weirs exist in a wide range of forms in the Don Catchment.

$$H_n = H_w - \frac{Q_n}{H_{factor}} \qquad (8.3)$$

where H_w = the height of a weir from its crest to the river bed at the foot of the weir at its downstream side (Sheffield Renewables 2008).

Values for $Qmax_n$ were obtained from the National River Flow Archive for Hadfield's Weir which is used by the EA to gauge river flow. For the rest of the weirs in the Don Catchment, the Shreve score (a measure of stream order) (Shreve 1966) of the river where a weir is situated was used to estimate flow. The Shreve score of a river was assumed to be proportionate to its flow, so for example, if a river had a Shreve score of ten, then it was assigned a flow that would be double that of a river with a Shreve score of five. The correlation of Shreve scores with river flow is not going to be exact due to a number of confounding factors. For example, one stream in the upper part of the catchment will receive more rainfall than one with the same Shreve score lower down in the catchment. This will increase the uncertainty in the output of the model, but as no flow exceedance data was available for other weirs then it was necessary to make an estimation.

Other sources of uncertainty are the capacity and efficiency values used in the modelling as these are specific to each type of microhydro scheme. There are a number of different microhydro options available in the Don Catchment, though Archimedes screw type schemes are the type most likely to be installed. Of microhydro three microhydro schemes on weirs known to exist in the region, two are Archimedes screw types, and of three schemes known to be planned in the Don Catchment, two are also Archimedes screw type. For this reason the efficiency and capacity of this Archimedes screws were used.

Additionally, other practical constraints such as the accessibility of the weir and proximity to the electricity distribution network limit the feasibility of installing microhydro. These are details that cannot be considered at a catchment-scale, so for each weir the installation of a microhydro scheme is assumed to be logistically practical. For the reasons above, the output of the model provides an indicative rather than accurate figure of the electricity a microhydro scheme could generate. This is compatible with a decision support system such as the Weir Tool which aims to give a strategic overview of the issues at a catchment-scale. Users can identify combinations of weir modifications that perform highly with regard to hydroelectricity output and other criteria, and afterwards then start the laborious task of making site visits to explore the feasibility of implementing their strategy. The microhydro model can be found on the CD that comes with this thesis.

Weir modification costs

Weir modification can be extremely expensive and the knowledge of the financial costs of different modification options is of great importance to decision makers. For a single weir modification type (e.g. the installation of an Alaskan A type fish pass), costs can vary greatly (Armstrong *et al.* 2010). This is because they are dependent on a wide variety of factors, such as the physical dimensions of the weir, the accessibility of the weir, its structural integrity, and the amount of consultancy required to assess the impact of the modification e.g. flood modelling. Much of this is information specific to each weir and an in-depth assessment is required to produce it. As the information determining the cost of modifying each weir was not available during the course of the study, nor was it practical to gather it for the >200 weirs that impound the Don Catchment, a generic cost for each weir modification was used (Table 8.1). These costs were derived from a variety of sources, including internet pages, EA documents and personal communication. Where multiple costs were found for the same modification type, then the mean cost was used. Where no costs were found, then a cost was estimated. The costs only had to be approximate as their function were to constrain the participants in the experiment (presented in chapter 6) during decision making, so they needed to be effective with what they spent their limited budget on.

Table 8.1. Weir modification costs used in the Weir Tool.

Weir modification	Cost (£)
Alaskan A fish pass	250,000
Plane baffle fish pass	250,000
Rock ramp	113,000
Pool and traverse fish pass	50,000
Rock baffle (Figure 1.5c)	1000
Weir notching	1000
Eel pass	33,000
Microhydro	275,000
Canoe Pass	100,000
Changing orientation of weir (Figure 1.2)	150,000
Changing weir height	70,000
Changing weir steepness	70,000
Removing a weir	50,000

Appendix b. The questionnaire used to elicit the probabilities from the canoeists to build the canoeing BN

The questionnaire comes in three parts that ask different types of question which are needed to interpolate the probabilities. The format of the questionnaire has been reduced in size to conserve paper use.

Questionnaire - Part 1

1. Estimate the influence of weir danger on the local river reach quality for canoeing

1.1 If the danger of a weir is low and weir fun and river context are in states that maximise local river reach quality, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20 improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

1.2 If the danger of a weir is medium and weir fun and river context are in states that maximise local river reach quality, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20 improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

1.3 If the danger of a weir is high and weir fun and river context are in states that maximise local river reach quality, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20 improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

2. Estimate the influence of weir fun on the local river reach quality for canoeing

2.1 If the fun canoeing on a weir is high and weir danger and river context are in states that maximises local river reach quality, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20
improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

2.2 If the fun canoeing on a weir is medium and weir danger and river context are in states that maximises local river reach quality, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20
improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

2.3 If the fun canoeing on a weir is low and weir danger and river context are in states that maximises local river reach quality, how likely is it that local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20
improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

3. Estimate the influence of river context on the local river reach quality for canoeing

3.1 If a river is an upland fast flowing river and weir danger and fun are in a state that maximises local river reach quality, how likely is it that the local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20
improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

3.2 If a river is an intermediate flowing river and weir danger and fun are in a state that maximises local river reach quality, how likely is it that the local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

3.3 If a river is a slow flowing river and weir danger and fun are in a state that maximises local river reach quality, how likely is it that the local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

4. Estimate the influence of drawback danger on weir danger

4.1 If drawback danger below a weir is low, and presence of a fish or canoe pass and risk of physical damage are in states that are least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

4.2 If drawback danger below a weir is medium, and presence of a fish or canoe pass and risk of physical damage are in states that are least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

4.3 If drawback danger below a weir is high, and presence of a fish or canoe pass and risk of physical damage are in states that are least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

5. Estimate the influence of the presence of canoe pass or fish pass type on weir danger

5.1 If a weir has a canoe pass and the drawback danger and risk of physical damage are in states that are least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

5.2 If a weir has a chutable fish pass and the drawback danger and risk of physical damage are in states that are least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

5.3 If a weir has neither a chutable fish pass nor canoe pass and the drawback danger and risk of physical damage are in states that are least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

6. Estimate the influence of the risk of sustaining physical damage chuting on weir danger

6.1 If the risk of sustaining physical damage chuting a weir is low and the presence of a chutable fish/canoe pass and drawback danger are in states least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

6.2 If the risk of sustaining physical damage chuting a weir is medium and the presence of a chutable fish/canoe pass and drawback danger are in states least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

6.3 If the risk of sustaining physical damage chuting a weir is high and the presence of a chutable fish/canoe pass and drawback danger are in states least dangerous, how likely is it that weir danger will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

7. Estimate the influence of weir plane on drawback danger

7.1 If the plane of a weir is perpendicular and that the size of the drawback, the size of the stopper and the presence of an egress point are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

7.2 If the plane of a weir is oblique and that the size of the drawback, the size of the stopper and the presence of an egress point are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

7.3 If the plane of a weir is broken and pointing upstream and that the size of the drawback, the size of the stopper and the presence of an egress point are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

7.4 If the plane of a weir is broken and pointing downstream and that the size of the drawback, the size of the stopper and the presence of an egress point are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

7.5 If the plane of a weir is 'smiling' and the size of the drawback and that the size of the drawback, the size of the stopper and the presence of an egress point are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

7.6 If the plane of a weir is 'frowning' and the size of the drawback and that the size of the drawback, the size of the stopper and the presence of an egress point are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

8. Estimate the influence of drawback size on drawback danger

8.1 If the size of drawback at a weir is small and that the plane of a weir, the presence of an egress point, and size of the stopper are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

8.2 the size of drawback at a weir is medium and that the plane of a weir, the presence of an egress point, and size of the stopper are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

8.3 the size of drawback at a weir is large and that the plane of a weir, the presence of an egress point, and size of the stopper are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

9. Estimate the influence of the size of the stopper on drawback danger

9.1 If the size of the stopper at a weir is small and that the plane of a weir, the presence of an egress point and size of the drawback are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

9.2 If the size of the stopper at a weir is medium and that the plane of a weir, the presence of an egress point and size of the drawback are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

9.3 If the size of the stopper at a weir is large that the plane of a weir, the presence of an egress point and size of the drawback are in states that minimise the danger of drawback, how likely is it that the danger of draw back will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

10. Estimate the influence of the presence of an egress point downstream on drawback danger

10.1 If a weir has an egress point immediately downstream and that the plane of the weir and size of the drawback and size of the stopper are in states that minimise the danger of drawback the danger of drawback, how likely is it that the danger of drawback will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

10.2 If a weir does not have an egress point immediately downstream and that the plane of the weir and size of the drawback and size of the stopper are in states that minimise the danger of drawback the danger of drawback, how likely is it that the danger of drawback will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

Questionnaire - Part 2

1. Estimate the relevance of impacts

1.1 If you wanted to predict the quality of a stretch of river for canoeing, on a scale of 0 to 10 how relevant are these variables:
Weir danger (a)
Weir fun (b)
The river context of the weir (c)

0 no relevance
2.5 low relevance
5 moderate relevance
7.5 high relevance
10 very high relevance

	Estimate	Range (optional)
a)		
b)		
c)		

Comments:

1.2 If you wanted to predict the overall danger of a weir, on a scale of 0 to 10 how relevant are these variables:
Drawback danger (a)
Presence of fish or canoe pass (b)
Risk of physical damage (c)

0 no relevance
2.5 low relevance
5 moderate relevance
7.5 high relevance
10 very high relevance

	Estimate	Range (optional)
a)		
b)		
c)		

Comments:

1.3 If you wanted to predict the <u>danger</u> of a weir's drawback, on a scale of 0 to 10 how relevant are these variables:
Weir plane (a)
Drawback size (b)
Stopper size (c)
Presence/absence of egress point downstream of weir (d)

0 no relevance
2.5 low relevance
5 moderate relevance
7.5 high relevance
10 very high relevance

	Estimate	Range (optional)
a)		
b)		
c)		
d)		

Comments:

2. Estimate the probabilities for states of local river reach quality for canoeing

2.1 If you know that weir danger is medium, weir fun is high and river context is an upland fast flowing river, how likely would you guess that the local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the river Don?

0 impossible
20
improbable
40
possible
60
probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

2.2 If you know that weir danger is low, weir fun is medium and river context is an intermediate river, how likely would you guess that the local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the river Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

2.3 If you know that weir danger is high, weir fun is low and river context is a slow flowing lowland river, how likely would you guess that the local river reach quality will be:

- excellent (a)
- good (b)
- medium (c)
- poor (d)
- very poor (e)

in the river Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		
d)		
e)		

! Estimates should add up to 100!

Comments:

3. Estimate the probabilities for states of weir danger

3.1 If you know that there is a canoe pass present in a weir, the danger of drawback is low, and the risk of receiving physical damage chuting a weir is low, how likely would you guess that the danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

3.2 If you know that there is a fish pass present in a weir, the danger of drawback is medium, and the risk of receiving physical damage chuting a weir is medium, how likely would you guess that the danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

3.3 If you know that there is neither a fish pass or canoe pass present on a weir, the danger of drawback is high, and the risk of receiving physical damage chuting a weir is high, how likely would you guess that the danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

4. Estimate the probabilities for states of drawback danger

4.1 If you know that the plane of a weir is broken so that it points upstream, the size of drawback is low, the size of the stopper is low, and that there is an egress point immediately downstream of a weir, how likely would you guess that the drawback danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

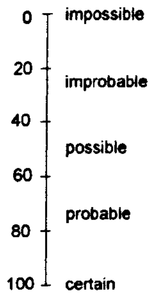
! Estimates should add up to 100!

Comments:

4.2 If you know that the plane of a weir is 'smiling' so that it points upstream, the size of drawback is low, the size of the stopper is low, and that there is an egress point immediately downstream of a weir, how likely would you guess that the drawback danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?



	Estimate	Range (optional)
a)		
b)		
c)		

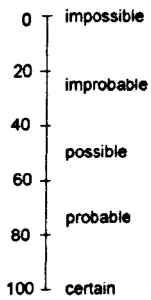
! Estimates should add up to 100!

Comments:

4.3 If you know that the plane of a weir is oblique, the size of drawback is medium, the size of the stopper is medium, and that there is an egress point immediately downstream of a weir, how likely would you guess that the drawback danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?



	Estimate	Range (optional)
a)		
b)		
c)		

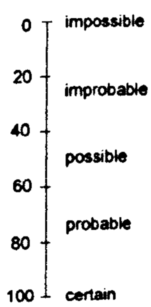
! Estimates should add up to 100!

Comments:

4.4 If you know that the plane of a weir is perpendicular, the size of drawback is medium, the size of the stopper is medium, and that there is no egress point immediately downstream of a weir, how likely would you guess that the drawback danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?



	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

4.5 If you know that the plane of a weir is broken so that it points downstream, the size of drawback is high, the size of the stopper is high, and that there is no egress point immediately downstream of a weir, how likely would you guess that the drawback danger of a weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

4.6 If you know that the plane of a weir is frowning so that it points downstream, the size of drawback is high, the size of the stopper is high, and that there is no egress point immediately downstream of a weir, how likely would you guess that the drawback danger of the weir will be:

- high (a)
- medium (b)
- low (c)

in the Don?

0 impossible
20 improbable
40 possible
60 probable
80
100 certain

	Estimate	Range (optional)
a)		
b)		
c)		

! Estimates should add up to 100!

Comments:

Appendix c. Documentation used alongside the questionnaire in during the probability elicitation process.

This documentation was provided to the canoeists during the probability elicitation stage of the construction of the Bayesian Network (BN). It included the definitions of the BN variables. The document has been formatted to reduce its size.

Documentation of the model structure and definitions of the model variables for river canoeing quality

Network description

The final model structure that forms the basis for the questionnaire is shown in the Figure below. It comprises the most relevant variables for describing the quality of the river for canoeing identified by canoeing experts. The resulting model will be a model that can predict how modification to a weir will affect the local quality of the river for canoeing.

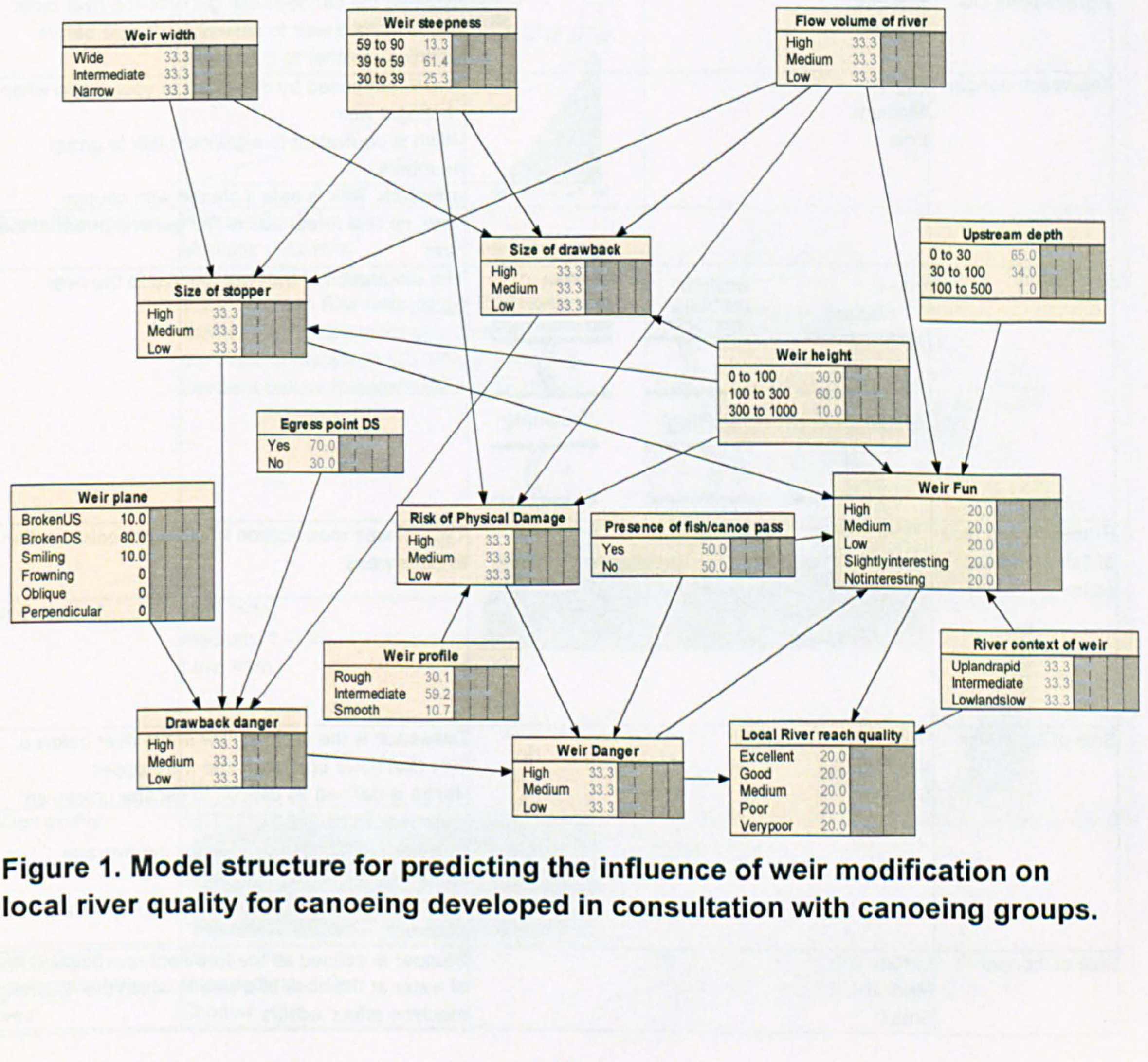
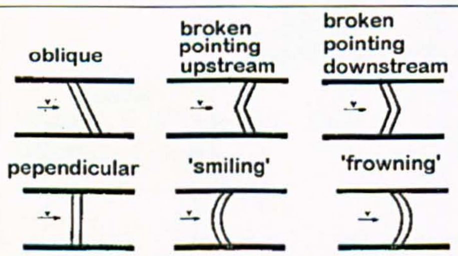
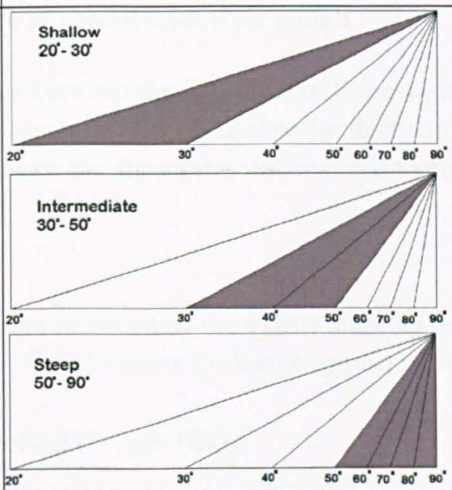
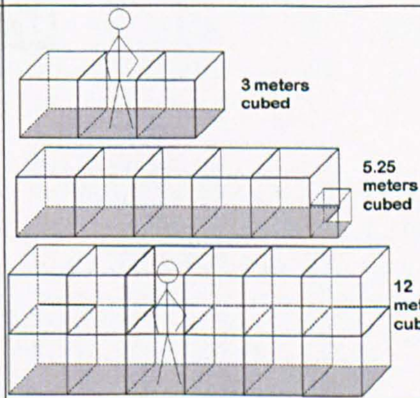
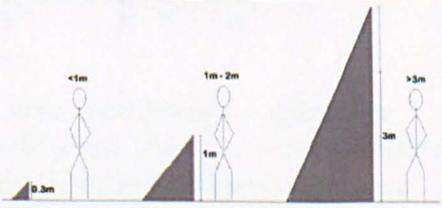
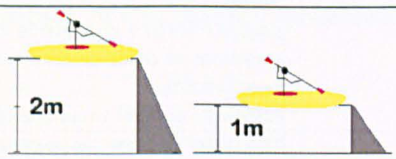


Figure 1. Model structure for predicting the influence of weir modification on local river quality for canoeing developed in consultation with canoeing groups.

Table 1. Definitions of the model variables and their states.

Variable	Categories	Description
Local river reach quality	Excellent Good Average Poor Very poor	Your opinion of the quality of a river stretch 25m upstream to 25m downstream of a weir for the canoeing community, taking account the full range of abilities and interests -**excellent** is equivalent to an enjoyable highlight of a river trip; -**good**, an enjoyable stretch of river -**average**, not worse or better than most stretches of river -**poor**, a tolerable but below average stretch of river -**very poor**, a stretch of river so un fun it's to be avoided
Weir danger	High Medium Low	The threat posed by a weir to the canoeing community when chuted -**high** is equivalent to significant risk to group members -**medium,** weir is safe if chuted with caution -**low,** no real threat above the general threat of the river
Weir fun	High Medium Low	The potential fun a weir could provide -**high** is equivalent to an exciting or enjoyable weir to chute -**medium,** reasonable exciting or fun -**low,** not really exciting or fun
Egress point US	Present Absent	Whether the canoeist can get onto the river bank upstream of a weir to assess its danger before deciding whether to descend it.
Drawback danger	High Medium Low	The threat posed by drawback to your group when chuting a weir -**high** is equivalent to significant risk to group members, -**medium**, weir is safe if chuted with caution -**low**, no real threat above the general threat of the river
Weir plane		The orientation of the weir relative to the river banks
Presence and type of fish or canoe pass		Type of weir modification to allow canoeists or fish to pass weirs
Size of drawback	Large Medium Small	Drawback is the surface flow of the river below a weir that flows upstream into the stopper -**large** is defined as difficult to escape unless an experienced canoeist -**medium**, difficult to escape for the average canoeist -**small**, not being a problem for the ordinary canoeist
Size of stopper	Large Medium Small	Stopper is defined as the turbulent recirculating flow of water at the base of a weir in which the 'washing machine effect' occurs

		-**large** is defined as a serious drowning hazard if caught without a boat inside it -**medium** as could cause drowning, especially in poor swimmers -**small** as in most circumstances no real threat
Weir width	Wide: >60m Intermediate: 30 – 60m Narrow: <30m e.g. the River Wyre at Garstang is approximately 20m wide, the River Ribble as the M6 crosses it South of Preston is approximately 70m wide	The distance from the point where the weir abuts one river bank to the point it abuts the river bank at the other side
Risk of physical damage	High Medium Low	The risk of sustaining physical injury when chuting a weir due to the physical forces involved -**high** is defined as it is likely that injury will be sustained -**medium** as a reasonable chance -**low** as unlikely
Weir steepness		The angle of the weir relative to the river bed
River flow volume	High: >12 m^3s^{-1} Medium: 3-12 m^3s^{-1} Low: <3 m^3s^{-1} e.g. The mean flow rates of the Ribble at Salmesbury is approximately 33 m^3s^{-1}, the Wyre at Garstang is 3.37m^3s^{-1}, and the Derwent bellow Bassenthwaite is 16.5m^3s^{-1}	
Weir height	High: >3m Medium: 1 – 3m Low: <1m	
Weir profile	**Large steps >1m Small steps<1m Approx smooth** 	The degree the weir is of a stepped shape in terms of step height
River depth upstream of the weir	Deep: >2m Intermediate: 1-2m Shallow: <1m	The approximate depth (acknowledging it is very variable) for the 10m upstream of a weir

		
River context of weir	Upland fast flowing Intermediate Lowland slow flowing	The river type the weir is set in.

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Appendix d. The questionnaire distributed to European eel experts to elicit estimations on the importance of factors in determining habitat quality for the European eel

Expert judgement on the importance of factors that determine habitat quality for the European eel (*Anguilla anguilla*)

Four variables used to derive a river habitat quality score for eel in terms of productivity:

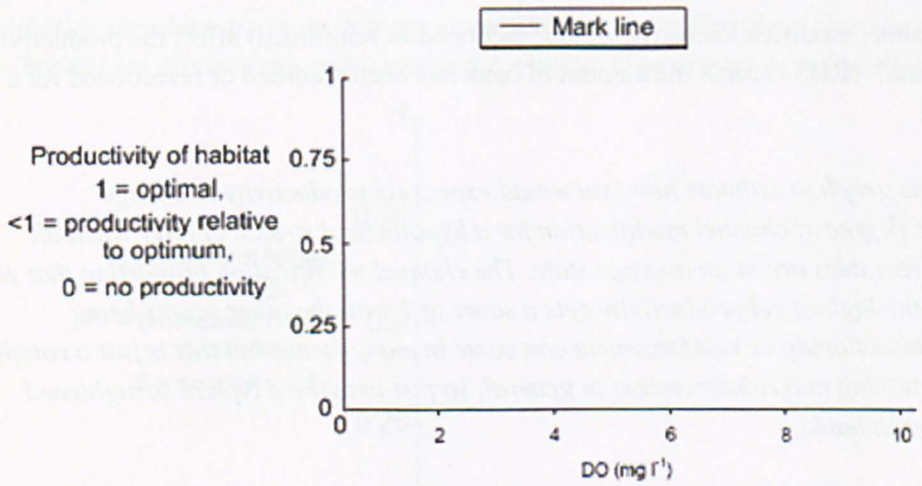
- RHS survey attributes (Degree of channel modification, substrate diversity, flow diversity and macrophyte cover) to create an overall RHS score
- Chemistry GQA scores (indicator of water quality)
- Phosphorus GQA scores (indicator of habitat productivity)
- Distance of habitat from river mouth

The relationships between the first three of these variables and habitat productivity aren't available in the literature. However expert judgement can give a rough estimate of these relationships. Hence the aim of this document is to elicit these expert judgements.

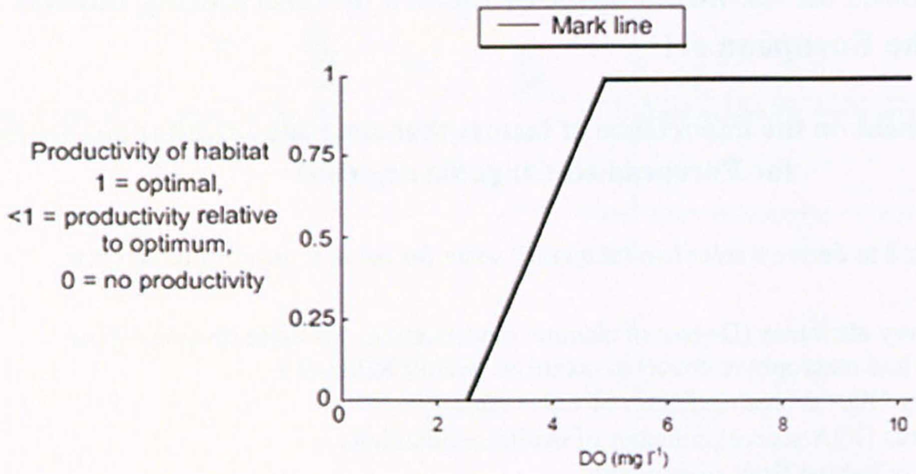
Instructions:

The weightings are recorded by the expert marking how they expect the productivity of river habitat in terms of eel biomass to change against a predictive variable.

Example -Dissolved Oxygen (DO)



The expert guesses how the productivity of a river habitat in terms of eel biomass is affected by different dissolved oxygen concentrations by marking this on the graph. The score of 1 is awarded to the concentrations that would result in the highest eel productivity, to which the other scores are relative e.g. a score of 0.5 is represents a habitat productivity approximately half that of the optimum. Obviously many different variables are important in determining habitat productivity but in this case we are only interested in DO so we consider them as being in an average state. The scores are just informed guesses and it is not important that they are exact. Instead they give an approximate estimate of the relationship between eel productivity and environmental variables, which together can create a rough habitat score indicating habitat productivity.



The line marked on the graph shows the expert expects DO concentrations below 2.5mgl^{-1} not to be sufficient to support any eel productivity. Above this threshold, the expert guesses productivity to increases rapidly until 5mgl^{-1} where the highest productivity is reached. Beyond 5mgl^{-1} the line plateaus showing that the expert predicts that productivity does not increase further or decline with higher DO concentrations.

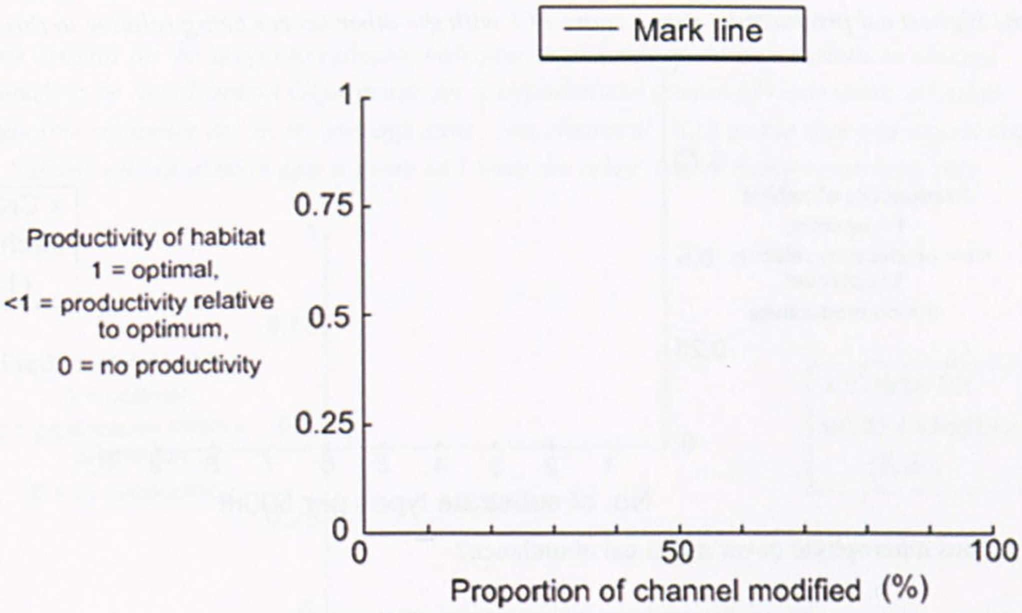
Questions to determine the relative importance of these factors:

Part 1. RHS scores

a.) How does channel modification (proportion resectioned or reinforced) affect the productivity of a habitat for eels? (RHS records the amount of bank has been recorded or resectioned for a stretch of river)

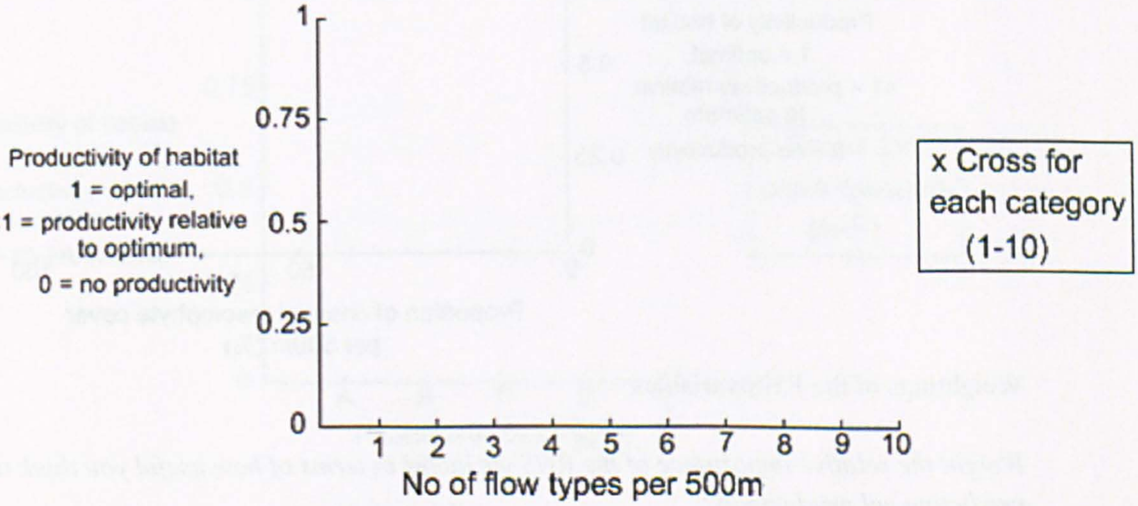
Mark a line on the graph to estimate how you would expect eel productivity to change depending on the degree of channel modification for a hypothetical stretch of river when all other predictive variables are in an average state. The channel modification proportion that you expect will have the highest eel productivity gets a score of 1 with the other scores being relative to this. Resectioning or reinforcement can come in many forms, but this is just a rough estimate of resectioning and reinforcement in general, so just imagine a typical straightened river with reinforced banks.

To draw the line copy the graph into 'Paint' under 'Accessories' on the 'Programmes' menu, use the line tool to mark the line on the graph, and copy back into this word document.



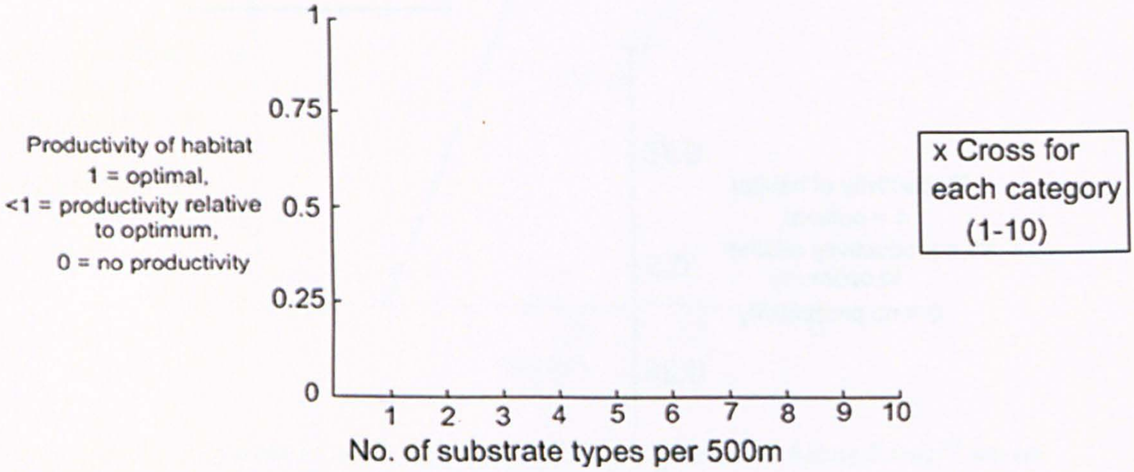
b.) How does flow diversity affect eel abundance? (RHS records the number of river flow types e.g. smooth, chaotic for a stretch of river)

Mark crosses on the graph to estimate how you would expect eel productivity to change depending on the number of flow types for a hypothetical stretch of river when all other predictive variables are in an average state. The number of flow types that you expect will have the highest eel productivity gets a score of 1 with the other scores being relative to this.



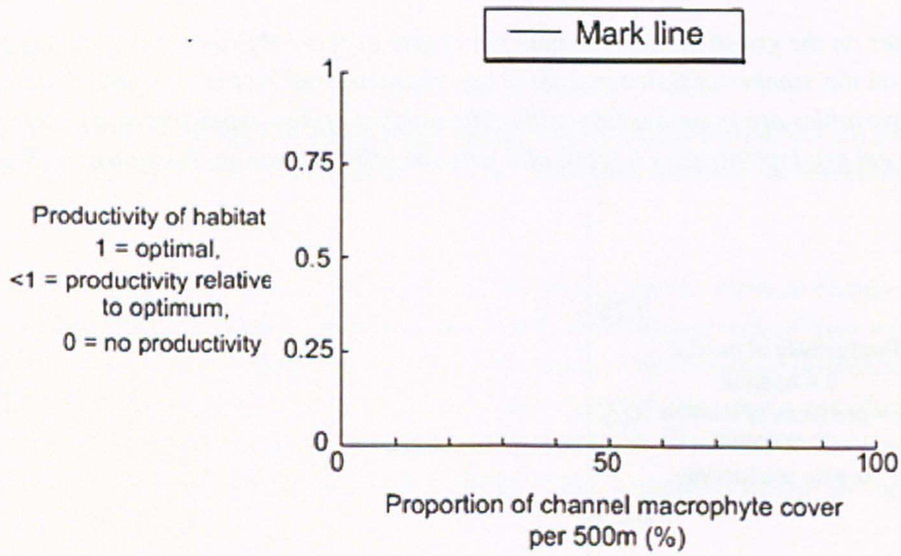
c.) How does substrate diversity affect eel abundance? (RHS records the number of river flow types e.g. smooth, chaotic for a stretch of river)

Mark crosses on the graph to estimate how you would expect eel productivity to change depending on the number of substrate types for a hypothetical stretch of river when all other predictive variables are in an average state. The number of substrate types that you expect will have the highest eel productivity gets a score of 1 with the other scores being relative to this.



d.) How does macrophyte cover affect eel abundance?

Mark a line on the graph to estimate how you would expect eel productivity to change depending on the proportion of macrophyte cover for a hypothetical stretch of river when all other predictive variables are in an average state. The proportion of macrophyte cover that you expect will have the highest eel productivity gets a score of 1 with the other scores being relative to this.



Weightings of the RHS variables

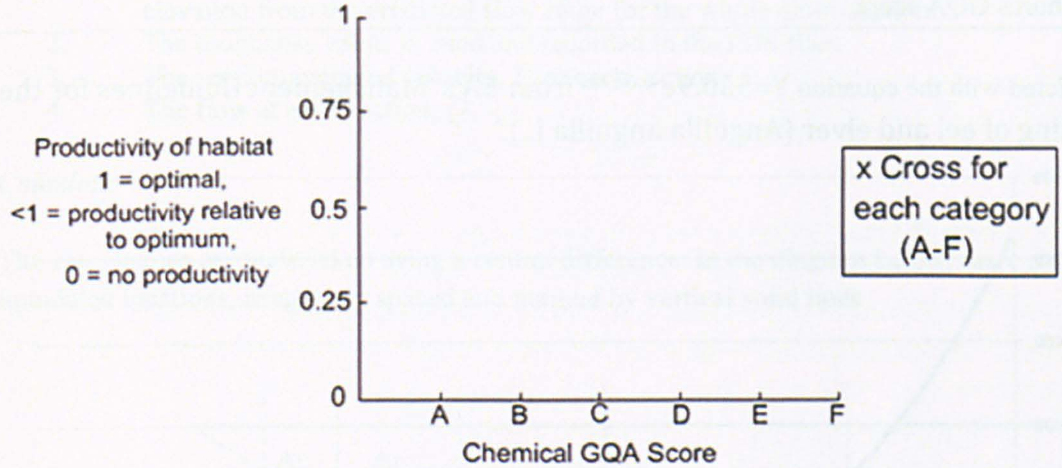
Weight the relative importance of the RHS variables in terms of how useful you think they are in predicting eel productivity:

RHS variable	Weighting (1-10)
Proportion of channel modification	
Flow diversity	
Substrate diversity	
Proportion of macrophyte coverage	

Part 2. Chemical and P GQA scores

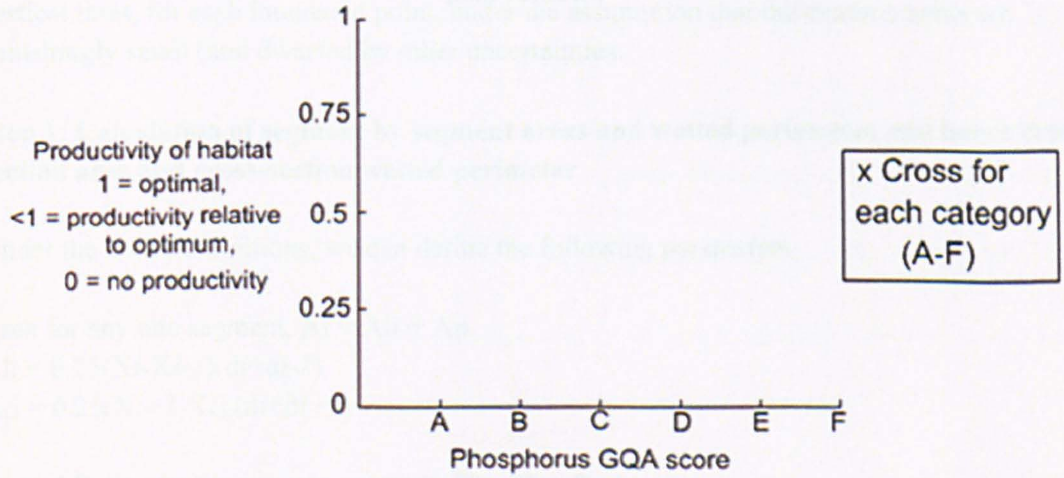
a). How does chemical water quality affect eel abundance?

Mark crosses on the graph to estimate how you would expect eel populations to change depending on the chemical GQA grade for a hypothetical stretch of river when all other predictive variables are in an average state. The chemical GQA grade that you expect will have the highest eel population gets a score of 1 with the other scores being relative to this.



b). How does P GQA scores (assumed surrogate for productivity) affect eel abundance?

Mark crosses on the graph to estimate how you would expect eel productivity to change depending on the phosphorus GQA grade (surrogate for productivity) for a hypothetical stretch of river when all other predictive variables are in an average state. The phosphorus GQA grade that you expect will have the highest eel productivity gets a score of 1 with the other scores being relative to this.

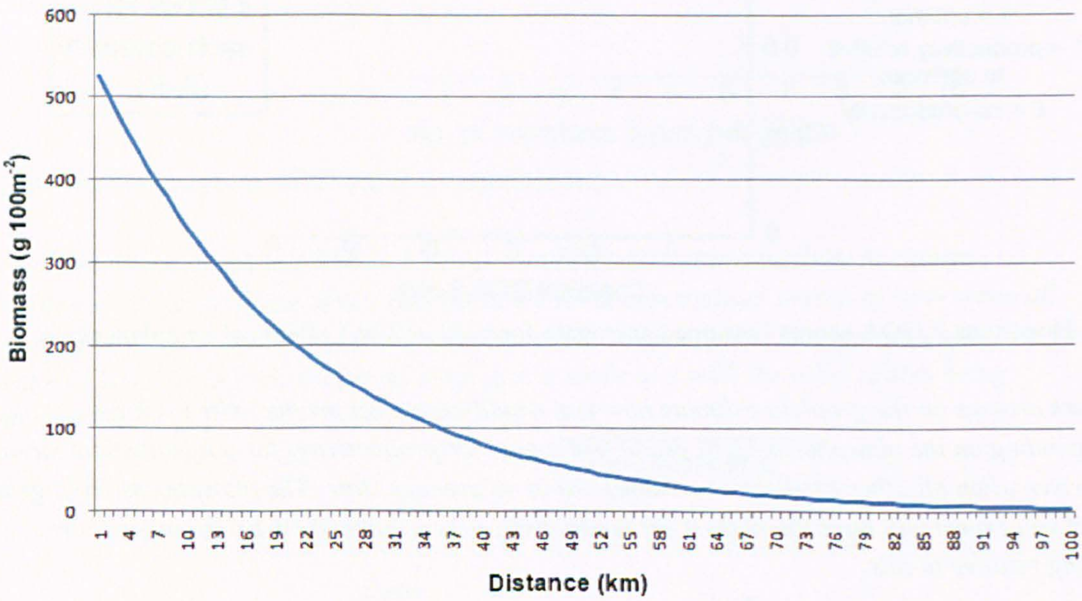


Weightings

Weight the relative importance of the variables in terms of how useful you think they are in predicting eel productivity::

Variable	Weighting (1-10)
Total RHS score	
Distance from river mouth*	
Chemical GQA score	
Phosphorus GQA score	

*Predicted with the equation $Y=550.9e^{-0.0478x}$ from EA's 'Management Guidelines for the Stocking of eel and elver (Anguilla anguilla L.).'



Appendix e. Methodology for distributing depth and velocity across an ISIS section provided by S Lane and C Brookes.

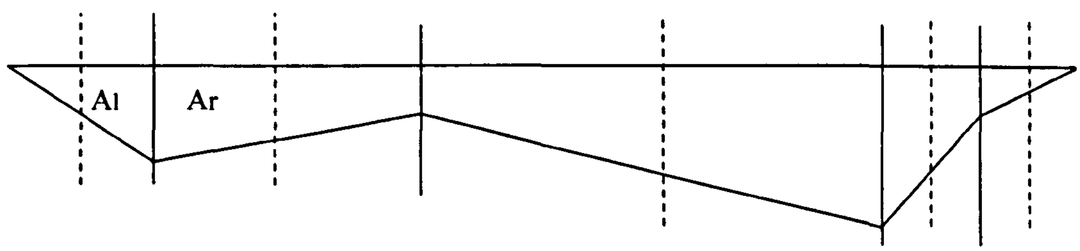
Data

Data needed:

1. Water depth, d, at each node, x, determined by subtracting each inundated node elevation from the predicted flow stage for the whole cross-section.
2. The roughness value, n, used and recorded in the ISIS files.
3. The section-averaged velocity, V, at each section.
4. The flow at each section, Q

Calculation

The calculations are undertaken using a central difference. In the diagram below, there are four inundated locations, irregularly spaced and marked by vertical solid lines



The dashed lines mark the halfway locations (by width or depth, no difference) between each of the inundated points. Thus, the calculation is performed for the area between each of the dashed vertical lines, for each inundated point, under the assumption that the extreme areas are vanishingly small (and dwarfed by other uncertainties.

Step 1: Calculation of segment by segment areas and wetted perimeters and hence cross-section area and cross-section wetted perimeter

Under the above definitions, we can define the following parameters

Area for any one segment, Ai = Ali + Ari
Ali = 0.25(X*i*-X*i-1*)(d*i*+d*i-1*)
Ari = 0.25(X*i+1*-X*i*) (d*i*+d*i+1*)

Wetted Perimeter for any one segment, Pi = Pli + Pri
Pli = [([0.5(Xi-Xi-1)]^2)+ ([0.5(di-di-1)]^2)]^0.5
Pri = [([0.5(Xi+1-Xi)]^2)+ ([0.5(di+1-di)]^2)]^0.5

If we sum Ai for all segments, we get the total cross-sectional area Ac; and if we sum Pi for all segments, the total wetted perimeter Pc

Step 2: Work out the equivalent friction slope

We now know V, n, Ac and Pc and hence can calculate the equivalent friction slope Sf:

$Sf = [Vn/([Ac/Pc]^{0.67})]^2$

Step 3: Determination of flow through each segment i

We now work out the velocity for each segment i

$Qi = (Sf^{0.5})([Ai/Pi]^{0.67})/n$

Note that this equation needs to correct for n for segments at the channel margin, where n is increased, so if there are s segments, for i = 1 and i = s, n become Mn, where M is the marginal friction multiplier.

Step 4: Scaling of flow estimate

The true flow at each section, predicted by iSIS, Q, will commonly be different, normally lower, than the sum of the flows at each segment. Thus, we scale each Qi by multiplying each by (Q/sum(Qi)).

Step 5: Determination of velocity for each node

Finally, we determine the velocity for each node as

$Vi = Qi/Ai$

Step 6: We can then interpolate the bottom velocity

First, we estimate the roughness height as:

$yo = ((n/0.034)^6)/3000)$

Then we apply this into a friction equation

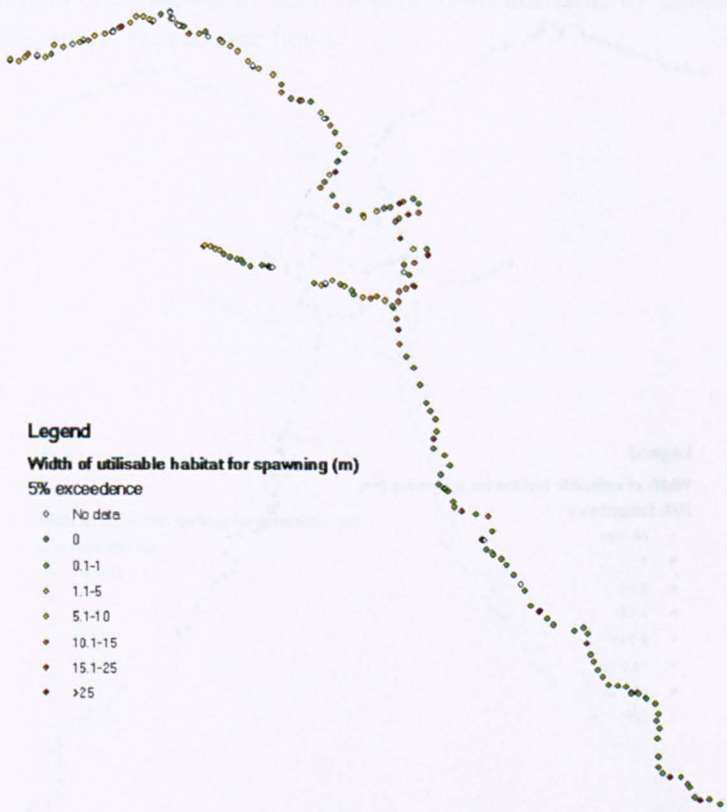
$Vzi = (2.5[(9.8(n^2))(Vi^2)/(di^{0.33})]^{0.5})\ln(z/yo)$

This introduces a user adjusted parameter, z, the height above the bed

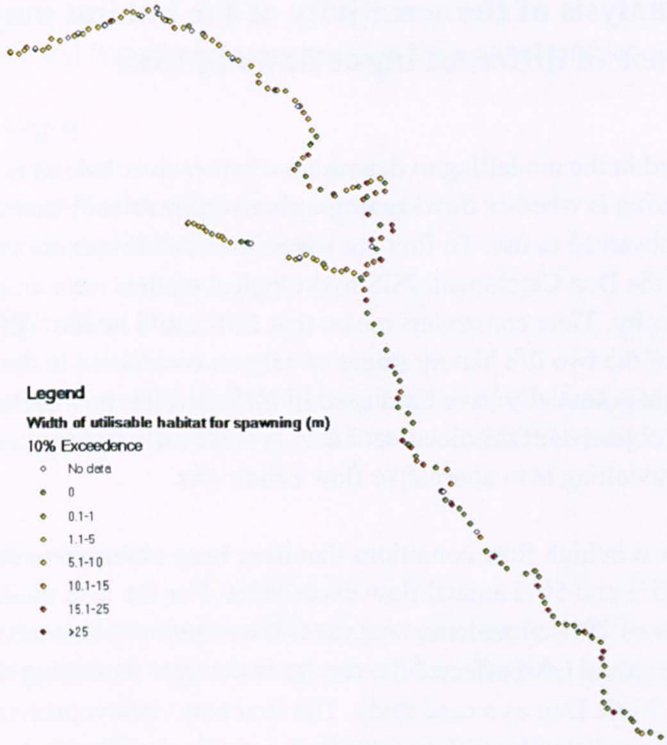
Appendix f. Analysis of the sensitivity of the habitat mapping for salmon to the use of different input flows in ISIS

One component used in the modelling to determine whether river habitat is utilisable by salmon for spawning or rearing is whether flow conditions are within velocity and depth limits that salmon have been observed to use. To find out where flow conditions are utilisable by salmon within the rivers in the Don Catchment, ISIS hydrological models were employed to calculate river depth and velocity. Time constraints meant that ISIS could be run with only one flow condition for each of the two life history stages of salmon considered in the modelling. Different flows could potentially have been used in ISIS, and this may influence the outcome of the modelling. The objective of this document is to present work undertaken to explore how sensitive the ISIS modelling is to alternative flow conditions.

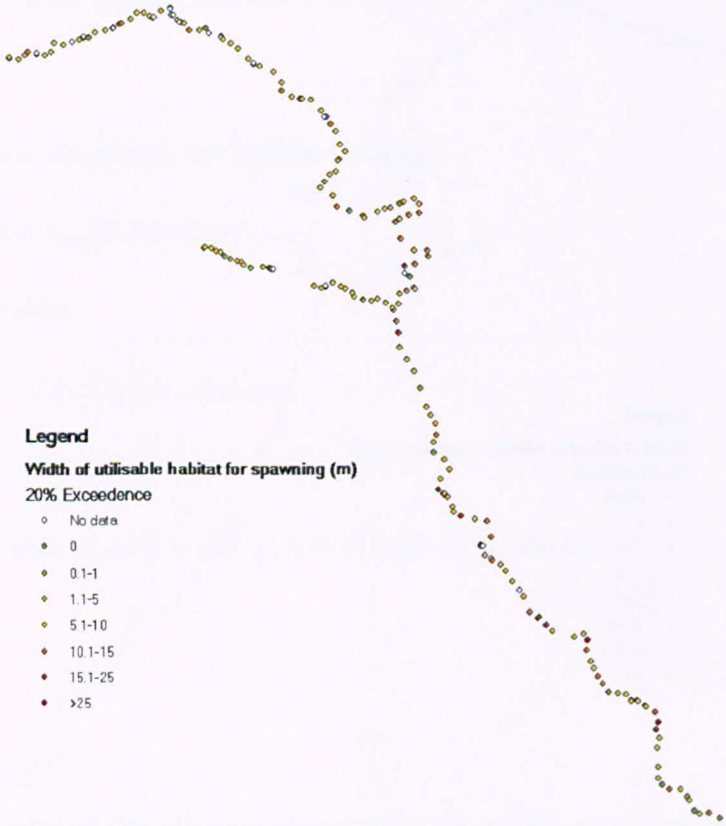
Salmon tend to spawn in high flow conditions that have been observed in one study river to be within the range of 5% and 50% annual flow exceedence. For the ISIS modelling in this project, an intermediate flow of 20% exceedence was used. We examine if flow conditions of 5%, 10%, 30%, 40% and 50% would have affected the results of the flow modelling taking the upper Don and its tributary the Little Don as a case study. The four maps below present the width of habitat at each cross section predicted by ISIS to have flow conditions utilisable by salmon for spawning for six different flow exceedence values within the range salmon have been observed to use:



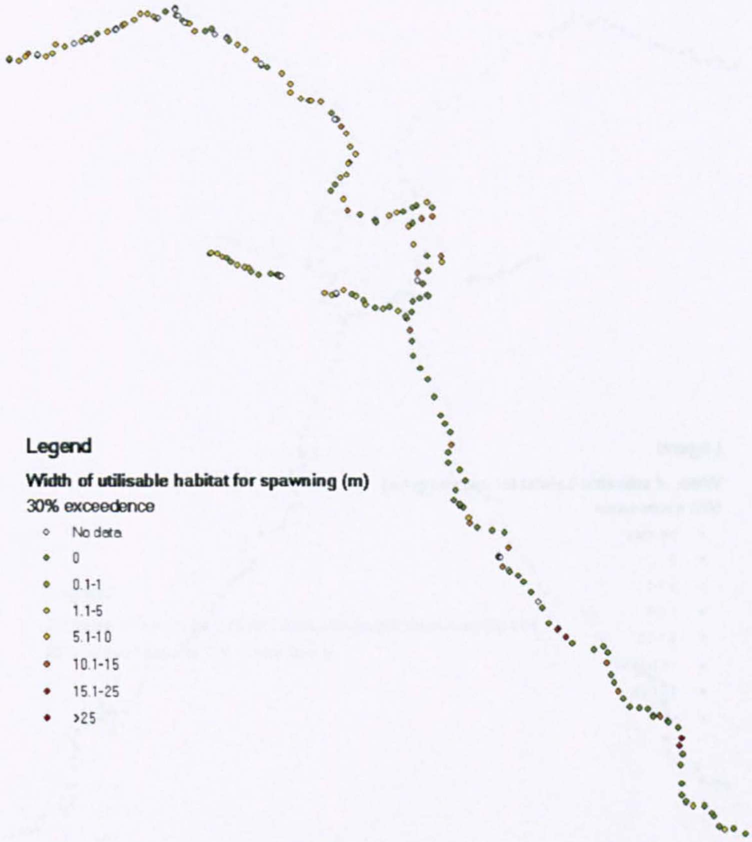
Width of habitat at ISIS cross sections with flow conditions utilisable by salmon for spawning modelled using 5% annual exceedence flows.



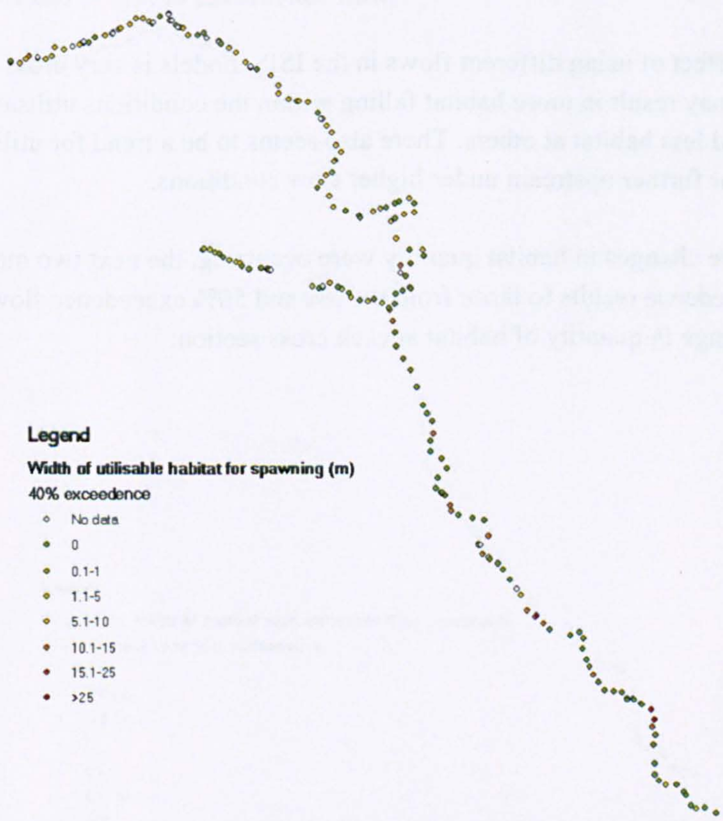
Width of habitat at ISIS cross sections with flow conditions utilisable by salmon for spawning modelled using 10% annual exceedence flows.



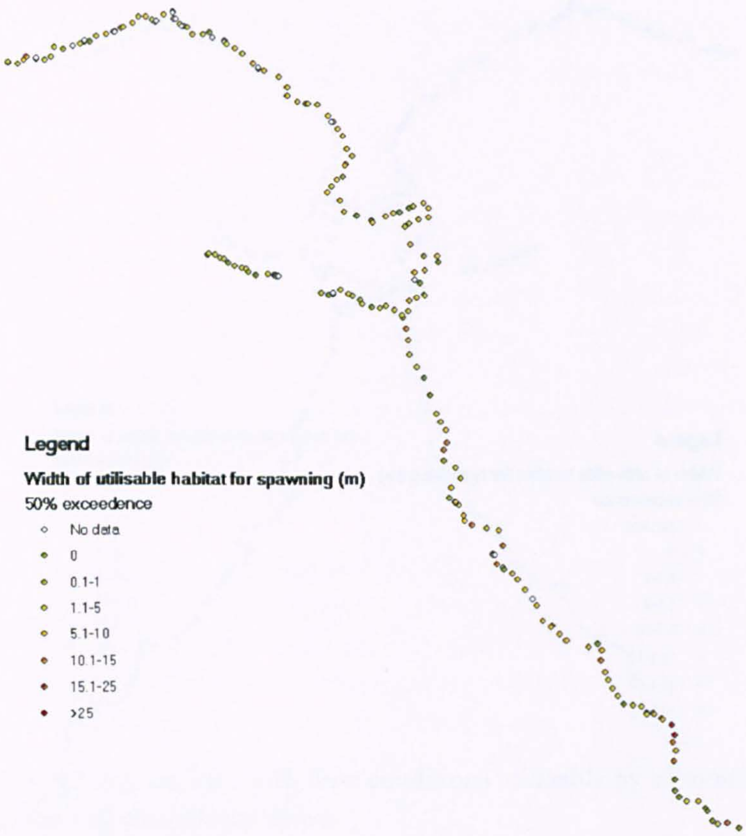
Width of habitat at ISIS cross sections with flow conditions utilisable by salmon for spawning modelled using 20% annual exceedence flows.



Width of habitat at ISIS cross sections with flow conditions utilisable by salmon for spawning modelled using 30% annual exceedence flows.



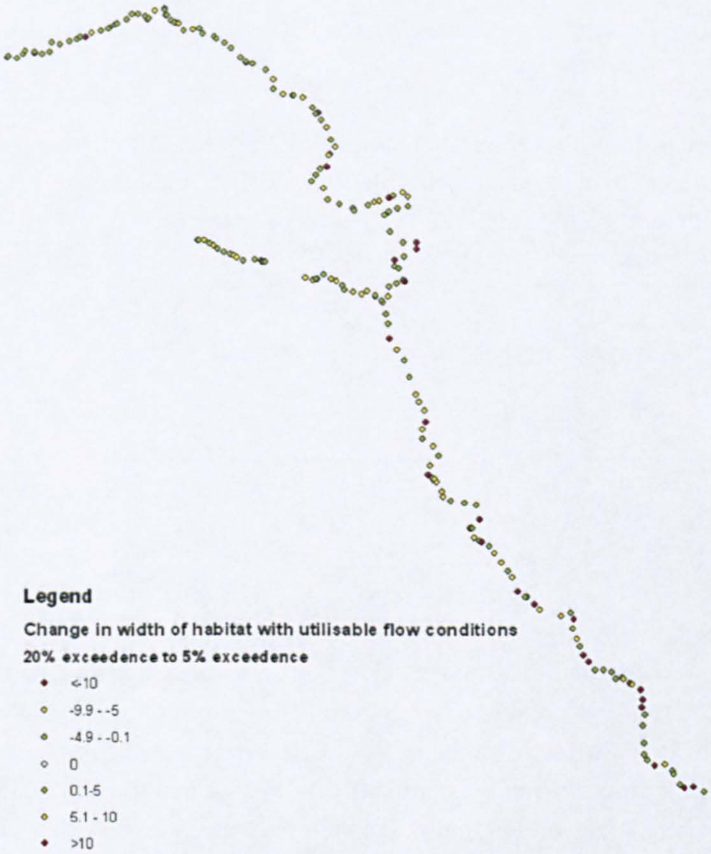
Width of habitat at ISIS cross sections with flow conditions utilisable by salmon for spawning modelled using 40% annual exceedence flows.



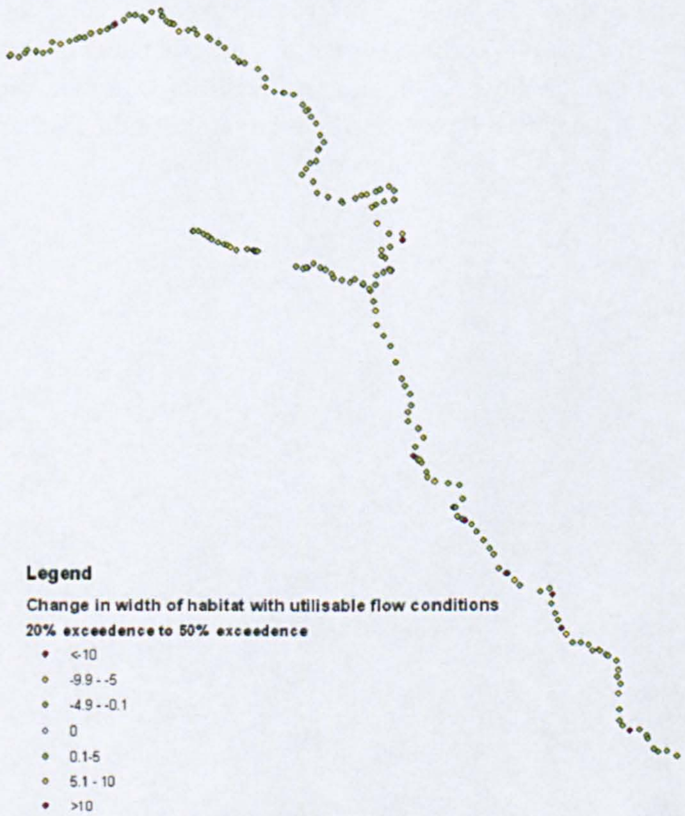
Width of habitat at ISIS cross sections with flow conditions utilisable by salmon for spawning modelled using 50% annual exceedence flows.

Comments: the effect of using different flows in the ISIS models is very cross section dependent. Increasing flow may result in more habitat falling within the conditions utilisable by salmon at some sections and less habitat at others. There also seems to be a trend for utilisable habitat to increasingly occur further upstream under higher flow conditions.

To examine where changes in habitat quantity were occurring, the next two maps compare the 20% annual exceedence results to those from the 5% and 50% exceedence flows in terms of magnitude of change in quantity of habitat at each cross section:



Magnitude of change of quantity of habitat at each cross section when using a 5% annual exceedence flow instead of a 20% exceedence flow.



Magnitude of change of quantity of habitat at each cross section when using a 50% annual exceedence flow instead of a 20% exceedence flow.

Comments: Most cross sections see small changes in the quantity of habitat, though a few see large changes.

To provide a picture of how overall predicted quantity of habitat in the upper Don is affected by different flows, the total habitat quantity for the five alternative exceedence flows are presented as a percentage of that predicted using the 20% exceedence flow:

Flow exceedence	5%	10%	30%	40%	50%
Quantity of habitat	81.6%	102.6%	57.1%	53.0%	71.7%

Conclusions:

The results generated by the ISIS modelling are sensitive to the flow used in the model hydrographs, both at individual cross sections, and at the river scale. This increases the caution we must use in interpreting the results arising from the modelling. Salmon have been observed to utilise flow conditions within the range of 5% to 50% in terms of flow exceedence. The distribution of usage within this range is unlikely however to be uniform, and is instead more likely to follow a normal distribution that is skewed towards the higher flows in the range. As the peak of this distribution probably lies between the 10%, 20% and 30% exceedence flows, then a 20% exceedence flow could well produce results representative of the overall year-to-year quantity of habitat available to salmon. This likelihood is also increased by the fact that at a catchment scale many rivers are unlikely to be sensitive to differences in flow. The upper Don has a large quantity of utilisable flow conditions, and the lower Don little, regardless of the exceedence flows used. Therefore it is expected that the results of the ISIS modelling are appropriate for the purposes of the work conducted in this project.