Project no.	**004074**
Project acronym:	**NATURNET-REDIME**
Project title:	**New Education and Decision Support Model for Active Behaviour in Sustainable Development Based on Innovative Web Services and Qualitative Reasoning**
Instrument:	**SPECIFIC TARGETED RESEARCH PROJECT**
Thematic Priority:	**SUSTDEV-2004-3.VIII.2.e**

D6.5.1-HIFI

Textual description for the UK case studies on the River Trent and Great Ouse focusing on the links between the ecological and socio-economic aspects of sustainable river rehabilitation and management

Due date of deliverable: **31/10/2006**
Actual submission date: **31/10/2006**

Start date of project: **1st March 2005** Duration: **30 months**

Organisation name of lead contractor for this deliverable:

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Revision [draft]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document history

Version	Status	Date	Author
1	Draft	23/10/06	R Noble
2	Final	30/11/06	R Noble

Content

Executive summary

This document contains the textual description of the NatureNet-Redime Qualitative Reasoning case study on rehabilitation of rivers for fish in the UK. The document contains the textual description of the QR prior to implementation and modelling within the GARP QR modelling platform. The document describes the two elements of the case study which covers a comparison of two rehabilitation issues in two different rivers (Trent and Great Ouse) in the UK. The document follows the NNR framework for model development (D6.1) and is broken down into system back ground (Section 2) initial specification (Section 3), global behaviour (Section 4) and detailed system structure (Sections 5 and 6).

The River Trent case study describes the rehabilitation activities required to re-establish a sustainable Atlantic salmon fishery. Up until the industrial revolution the River Trent used to support a large salmon population. However, the legacy of pollution and river modification for human use (e.g. navigation) lead to the extinction of a self sustaining salmon population. Given that recreational fisheries for Atlantic salmon have a high socio-economic value and also that self-sustaining salmon populations indicate that the river has a high ecological and conservation value a great amount of consideration and effort is being put into rehabilitating the River Trent to try and re-establish salmon stocks. This section of the case study models the rehabilitation scenarios and behaviours required to re-establish this species in the River Trent together with some of the socio-economic costs and benefits.

The Great Ouse case study describes the rehabilitation activities required to rehabilitate and improve ecological status and biodiversity of the floodplain of the Great Ouse. With the WFD there is a political drive to sustain good ecological status with all surface waterbodies in Europe. However, the Great Ouse has suffered a legacy of impacts and modification from navigation, land drainage and flood defence measures, and some parts of the lower catchments may not be considered to be at good ecological status. This part of the case study looks at some rehabilitation scenarios and behaviours for lowland floodplain rivers and how these will have ecological and socio-economic benefits.

Both case studies are built primarily around rehabilitation for fish, namely Atlantic salmon in the River Trent and common bream in the Great Ouse (with bream being used as a representative lowland species). The models look at how the rehabilitation measures are targeted to reduce population mortality and/or increase the capacity of the habitat to sustain a larger fish population.

1 INTRODUCTION

1.1 General objectives of the UK case studies

The Qualitative Reasoning (QR) case studies from the UK have four general objectives:

1. to develop qualitative reasoning models which can be used to show the links between the ecological and socio-economic aspects of sustainable aquatic resource management;
2. to use two case studies highlighting different river rehabilitation problems to show both the similarities and differences in potential solutions;
3. to show what actions are required for rehabilitation of two specific problems;
4. and to explore collaborative qualitative modelling approaches - building on experiences from the previous ecologically-based models.

1.2 Concepts of sustainable river management and rehabilitation in Europe

In general the overarching goal is to develop QR models that provide an educational tool for people who are learning about the issues of sustainable river management. These models will be developed in the light of the European Water Framework Directive - the overriding framework for the sustainable management of surface water resources in the European Union. The ecological and socio-economic issues of sustainable river management are highlighted in the concept map in Figure 1.1. Essentially sustainable river management can be defined as balancing the current socio-economic needs of utilising the ecosystem-services rivers can provide (water, hydropower, recreation etc.) with potential future needs and also targets for maintenance or improvement of ecological quality and integrity. Sustainable management of rivers is a complicated process that essentially requires sustainable catchment management as rivers can be seen to integrate all the impacts of all human activities and processes within and beyond the rivers catchment. Therefore, the Water Framework Directive formalises a river basin management planning approach - using a holistic approach to the sustainable management of surface water resources.

Within this management framework, rehabilitation activities can be seen as the amelioration of the impact of historical unsustainable human uses of rivers which have damaged both the ecological quality of the river and the potential of the river to be used for other human requirements in the future. Both sustainable river management and rehabilitation can only be undertaken successfully if there are both social/political (e.g. common societal goals for conservation of aquatic resources) and economic drivers (e.g. funding for rehabilitation or incentives to reduce unsustainable uses of rivers). The European Union Water Framework Directive (EU 2000) formalises the approach for sustainable surface water management in the EU, structuring the approach to balance the socio-economic aspects of the development of water resources against defined environmental goals for maintaining and improving the ecological status of surface waters. Within this framework is the development of a “programme of measures” which is targeted to rehabilitate the impact of current and historical activities which have degraded the ecology of waters across Europe.

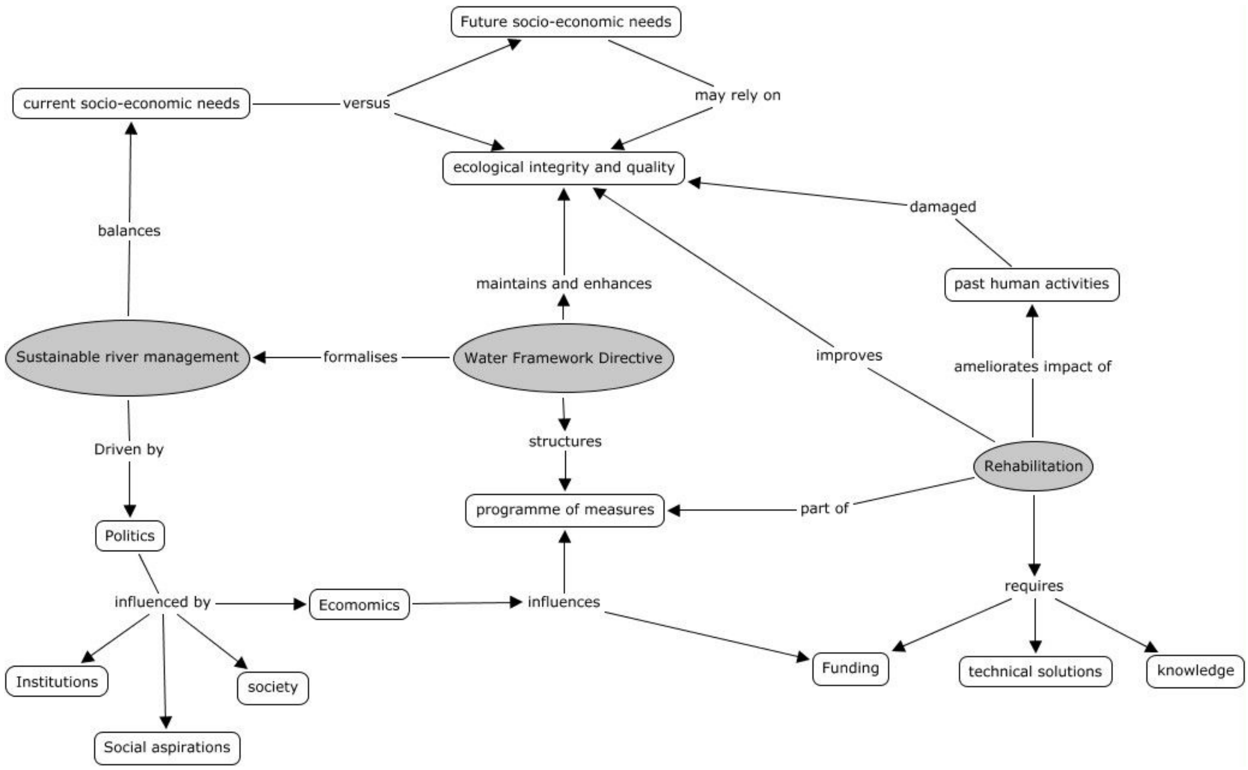

Figure 1.1 Concept map identifying the ecological and socioeconomic dimensions of sustainable river management and river rehabilitation.

In the case of the UK most large rivers have suffered a legacy of alteration and pollution that have resulted in losses of habitats and species, as well as the rivers capacity to provide clean water. As the historical legacy of the industrial revolution is slowly cleaned up the management of these rivers is beginning to address the rehabilitation of the ecological interests of these habitats, whilst also developing other water resource issues and services derived from them. These case studies will address two known rehabilitation issues in the UK. Firstly, the rehabilitation of Atlantic salmon (*Salmo salar* L.) populations in the River Trent (Sections 2, 3, 4 and 5) and, secondly, the rehabilitation of the Great Ouse a lowland floodplain river that has been impacted by channelisation and land drainage (Sections 2, 3, 4 and 6).

2 BACKGROUND TO THE RIVER TRENT AND GREAT OUSE CASE STUDIES

2.1 Background to Atlantic salmon rehabilitation in the River Trent

2.1.1 Rehabilitation problem and issues

The River Trent is 274 km long from its source on Biddulph Moor in north Staffordshire to its confluence with the Yorkshire Ouse and the Humber Estuary at Trent Falls (Figure 2.1). The River Trent is the third largest river in England and Wales, with a catchment area (10,500 km^2). Through its tributaries, the Trent drains a number of large conurbations, including Birmingham, Leicester, Derby, Stoke-on-Trent and Nottingham. The intense industrialisation and urbanisation associated with these areas following the industrial revolution led to deterioration in the water quality of the Trent.

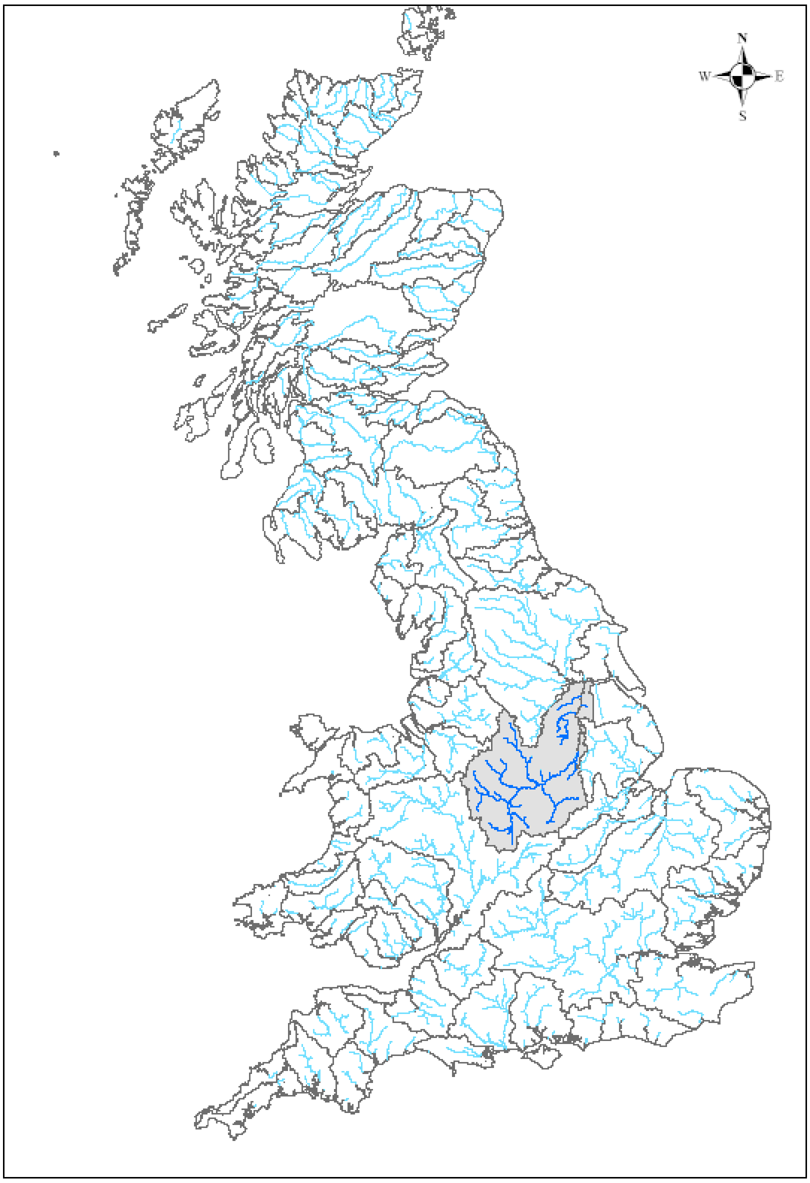

Figure 2.1 Location of the River Trent catchment which flows into the Humber estuary on the east coast of England, draining a large proportion of the Midlands. Catchment highlighted in grey and river channel highlighted in dark blue.

Prior to the industrial revolution, the Trent had diverse and prolific fish stocks, and supported salmon and eel (*Anguilla anguilla* (L.)) fisheries. However, with the expansion of industry, the fishery began to decline, and by 1920 the River Tame, a major tributary of the Trent, was devoid of fish. Water quality reached its lowest level in the 1950s, and long stretches of the Trent suffered from a lack of dissolved oxygen and were devoid of fish until the 1970s. Since the 1970's improvements in waste water treatment and management have led to great improvements in water quality to the point where these are no longer considered to be limiting factors to ecological recovery (Cowx 1986, Cowx & O'Grady 1995a, b, Sykes 2004).

In the past the River Trent was undoubtedly an important salmon river. Even in the late nineteenth century, when a large part of the catchment was already denied to salmon as a result of impassable barriers, records of salmon indicated that the Trent had a run of at least 3000 adult fish per year. The Trent was well known for its commercial salmon fisheries and there was also a notable rod and line fishery. The decline in catches from the 1880s onwards was almost certainly because of obstructions to the passage of migrating adult salmon and pollution (Cowx 1986, Cowx & O'Grady 1995a, b, Sykes 2004).

The River Trent and its tributaries contain many obstructions to the upstream passage of migratory fish. The vast majority were built at the time of the industrial revolution to supply power to the mills and create navigable waters for distribution of the produce, though some of the navigation weirs on the River Trent were reconstructed and enlarged in the 1920s to accommodate deeper draught vessels passing up to the city of Nottingham (Photo 1). The functions of watercourse obstructions were varied; they served to supply water or electrical power to mills and factories, to impound water for abstraction purposes, for the purpose of navigation, to alleviate flooding and for angling, aesthetic or amenity value. However, many of these obstructions now no longer serve the purpose for which they were originally intended due to changes in industry and navigation in the area. In recent times much consideration has been given to the potential to rehabilitate some of these semi-redundant weirs and to rehabilitate the salmon populations of the Trent (Cowx 1986, Cowx & O'Grady 1995a, b, Sykes 2004).

Photo 1 Holme Sluices at Nottingham on the River Trent - originally totally impassable to migrating fish until the construction of the canoe slalom fish pass (www.trentriverstrust.co.uk).

Much of the promotion of the potential rehabilitation of salmon populations lies around the fact that beyond their ecological and conservation value salmon fisheries may have a high social and economic value. However, whilst there are potential socio-economic benefits of re-establishing salmon populations to the Trent catchment, alterations to the longitudinal barriers on the Trent will have knock on effects to other user groups which may be considered detrimental to the continued development of other resources (navigation, water abstraction, hydropower generation, cultural heritage etc.). If salmon are re-introduced these conflicts between users (anglers, hydropower companies, water companies, historical societies etc.) will have to be resolved through negotiation with the various user groups (Figure 2.2). In addition, future proposals on the river will have to be evaluated to prevent degradation of the catchment and permit the sustained development of the salmon stocks.

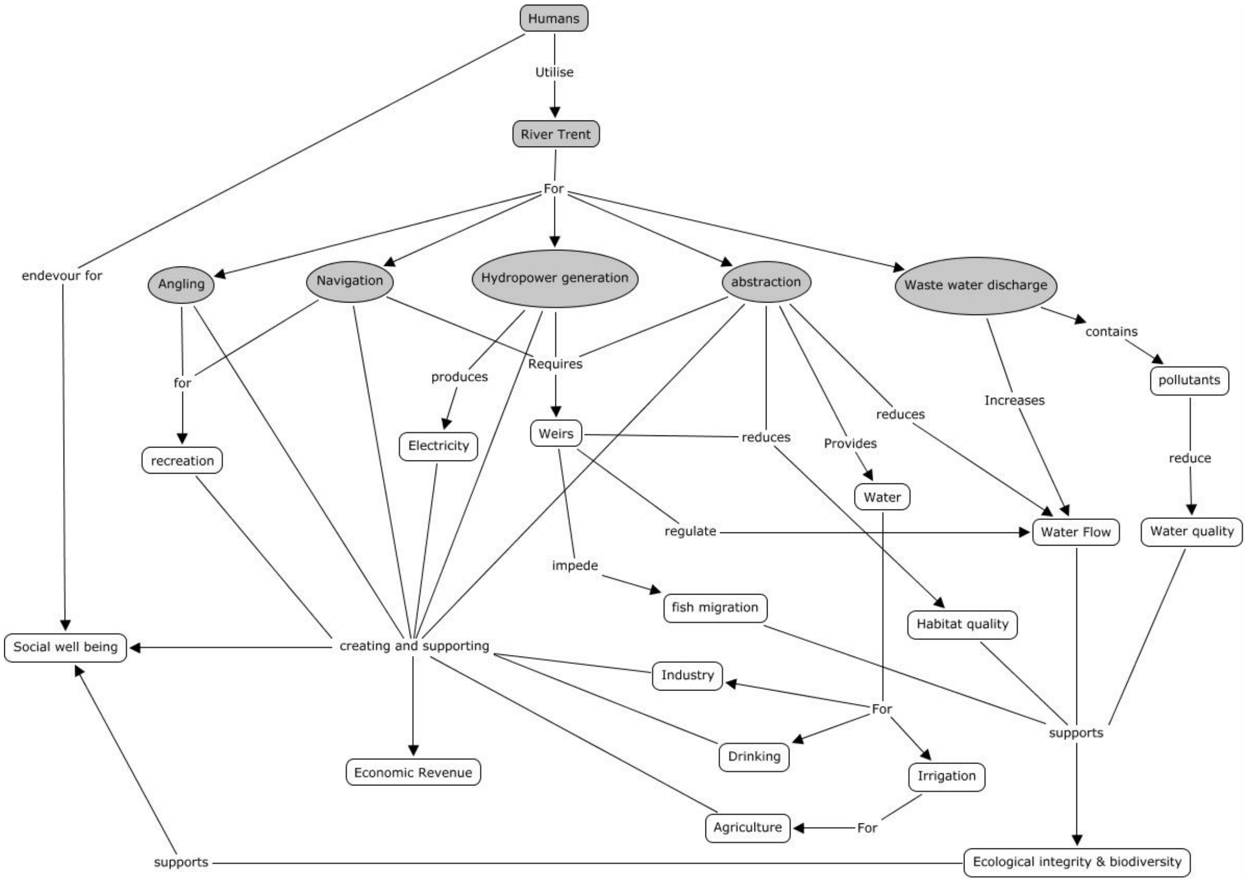

Figure 2.2 Concept map showing the various human uses of the River Trent and some of their socio-economic and ecological aspects.

Re-establishment of a self-sustaining population of Atlantic salmon in the River Trent requires a holistic approach that considers the ecological requirements of each life stage of the species together with the socio-economic aspects. Figure 2.3 shows the concepts that are related to the viability of a self-sustaining salmon population and fishery, related to the three major life stages of salmon; juvenile, smolt and adult.

Figure 2.4 highlights the key rehabilitation actions that will be necessary to re-introduce and re-establish a viable self-sustaining Atlantic salmon population and associated recreational fishery in the River Trent system. Each of these activities needs to be addressed in a holistic rehabilitation package to ensure success. Given that water quality is considered to now no longer be a limiting factor it is the management of flow regimes (the quantity of water) and the removal or by-passing of obstructions to allow migration of smolts and adults that are considered the most important aspects for rehabilitation.

2.1.2 Specific objectives for the River Trent case study

The qualitative reasoning model for the River Trent case study should provide an educational tool that:

1. enables investigators (managers, stakeholders, scientific researchers and students) to learn what activities are required to re-establish a salmon fishery in the River Trent;
2. shows the investigator the potential socio-economic benefits of re-establishing a fishery, together with the socio-economic costs of rehabilitation both to the fishery and other river users.

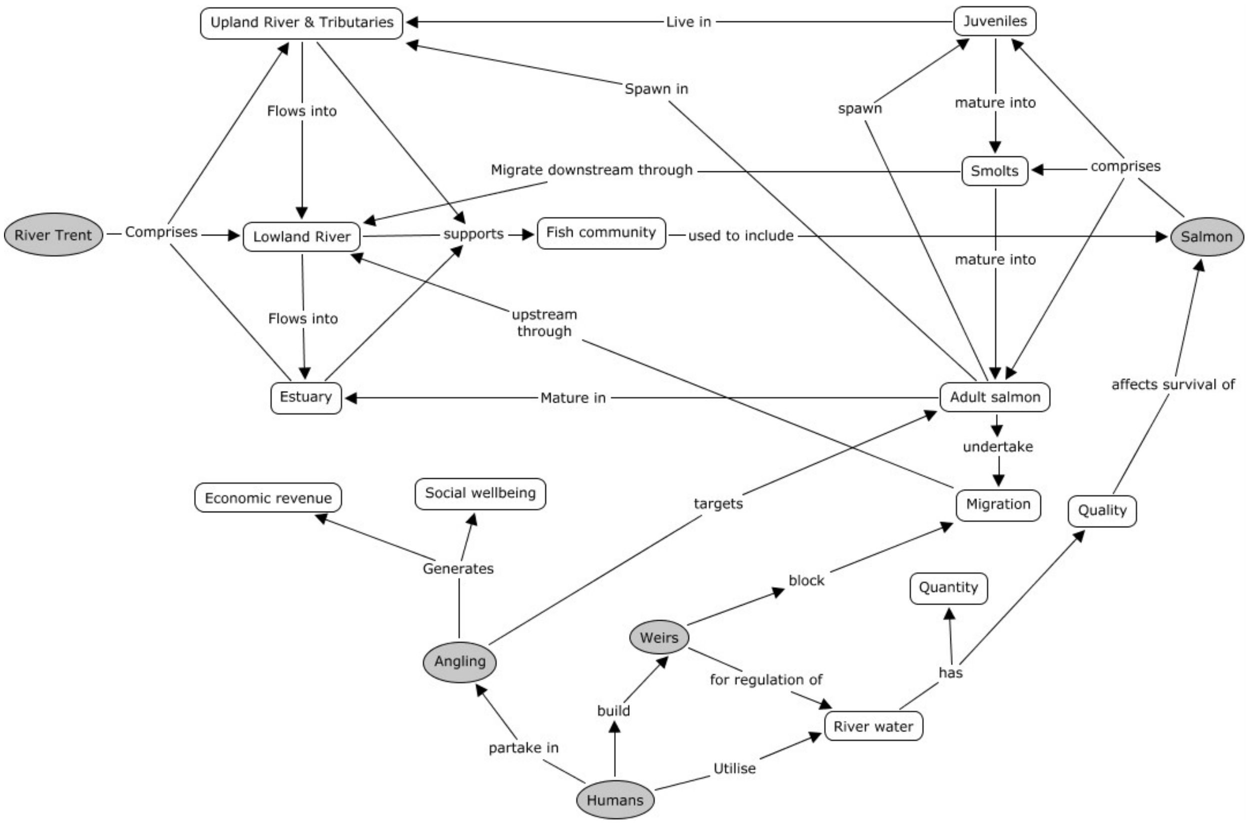

Figure 2.3 Concept map highlighting some aspects of the salmon life cycle in the context of angling and human use of the River Trent.

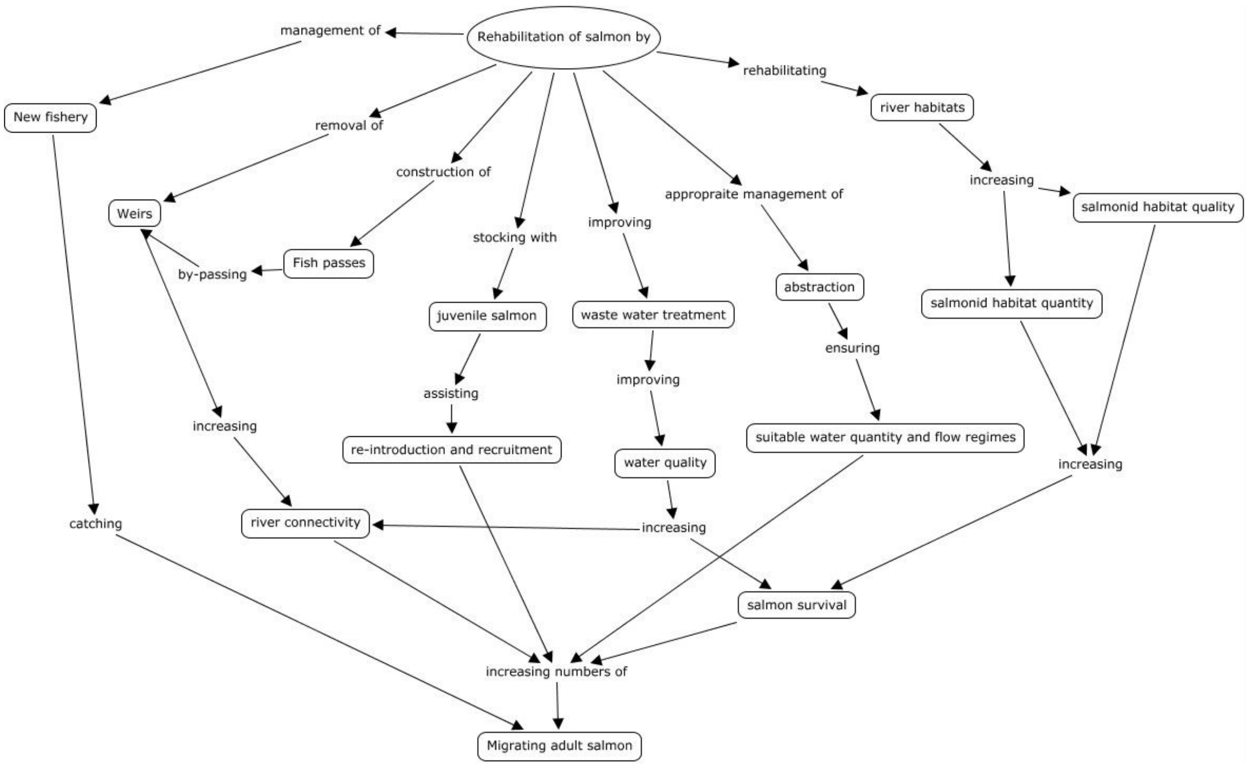

Figure 2.4 Rehabilitation activities required to re-introduce a viable salmon population and associated fishery in the River Trent.

2.2 Background to the Great Ouse case study

2.2.1 Rehabilitation problem and issues

The Great Ouse is one of the largest (8585 km^2) and driest river catchments in Eastern England, draining approximately 7% of England, covering much of East Anglia (Figure 2.5). The overall catchment extends from west of the headwaters, north-west of Buckingham in central England, to the Wash Estuary at King's Lynn. The main river length is 125 km. The lower part of the catchment is low-lying fenland (Cowx *et al.* 2004).

The Great Ouse catchment suffers from a legacy of channel modification and river regulation. During the 17th century, the Fens were transformed from wetlands with raised islands of clay, into productive arable land. The area is now covered by an extensive network of drainage channels varying in size from ditches to large waterways. Of particular note are the New Bedford River or Hundred Foot Drain, and Old Bedford River, which carry water between sluice complexes at Earith and Denver, bypassing much of the central part of the main river (not outside the catchment). These artificial channels are considered to be of high value for nature conservation, principally floodplain wash lands. Upstream of Bedford, regulation for flood control and resource management has been limited mainly to in-stream water retention (weir construction), land drainage (i.e. dredging, weed cutting) and the reclamation of abandoned meanders. Downstream of Bedford, regulation for small-craft navigation, as well as for flood control and water retention, has resulted in the loss of many flood meadows, oxbow lakes, etc. for agriculture or quarrying. This has resulted in a dredged and embanked main channel with few natural features (Cowx *et al.* 2004).

The predominately vertical banks along much of the lowland river, a result of land drainage, navigation and river regulation, have resulted in a lack of suitable marginal/riparian habitat for spawning and or for feeding and shelter of juvenile lowland river fish species. The lack of these off-channel floodplain types of habitats has detrimental consequences for fish recruitment and consequently consequences for angling interests and the wider ecological value of the river (Figure 2.7). Many fish species in lowland rivers make use of different riparian and connected floodplain water bodies during different life stages to enhance chances of survival (Cowx 2001). For example, fish may use off channel water bodies as refuge against high flow events, which in channelised systems can cause wash out of juvenile life stages (Figure 2.6) (Copp 1989, 1991, 1997). Common bream (*Abramis brama* L.) is a species which is indicative of large lowland rivers and is a species that makes use of connected floodplain water bodies during its life cycle. The species is also a common target for recreational anglers who fish in the lower Great Ouse catchment.

Assessment of the ecological status of the Great Ouse has highlighted the need to improve the health and ecological functioning of the Great Ouse ecosystem to ensure sustainability and preservation of fisheries and biodiversity (Cowx *et al.* 2004). One of the mechanisms identified for addressing this need is the reconnection of the back waters and side channels, which will provide a suitable platform for enhancing the fisheries and wildlife (Grift 2001, Grift *et al.* 2001a,b) (Figure 2.8). The recognition of the ecological value of wetland floodplain habitats together with the implementation of the Water Framework Directive for the sustainable management of river basins has resulted in holistic projects which attempt to integrate both conservation interests and the development of ecosystem services provided by the Great Ouse catchment. Within these projects the feasibility of re-establishing off-channel floodplain habitats has been considered to enhance the ecological quality of the Great Ouse catchment (Cowx *et al.* 2004).

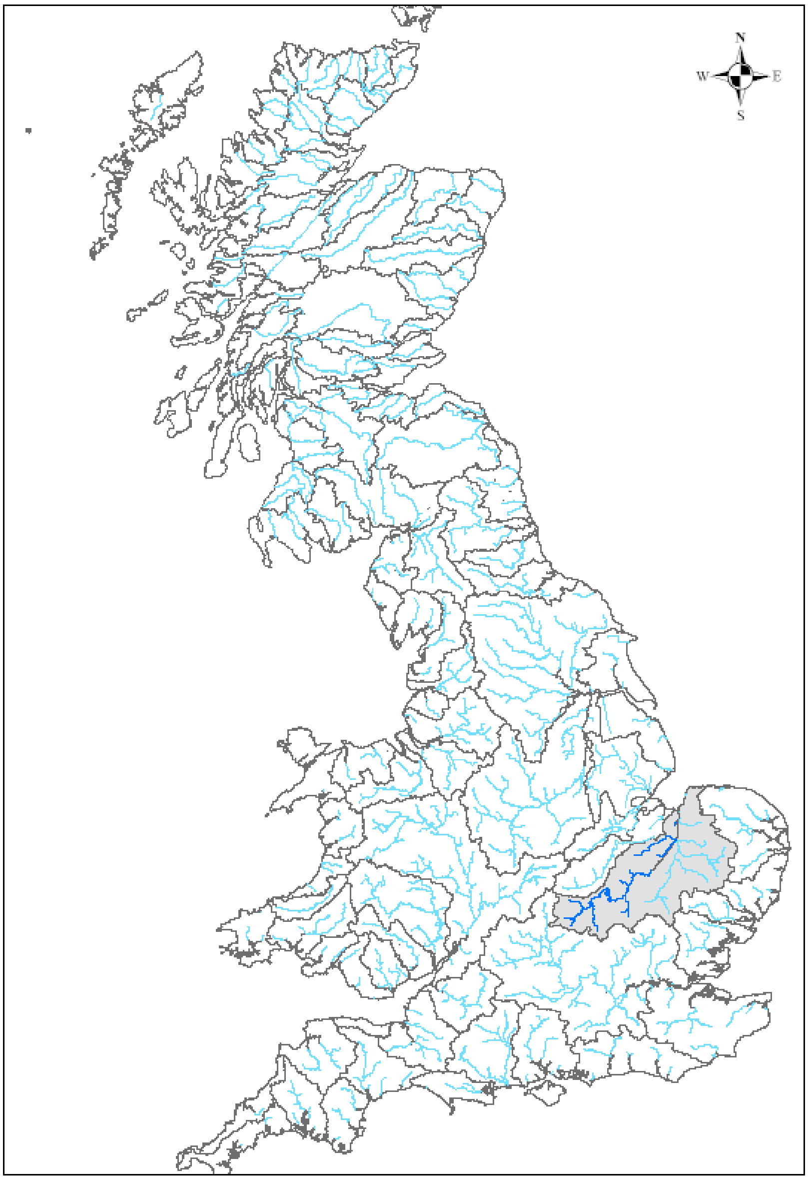

Figure 2.5 Location of the Great Ouse River catchment which flows into the Wash Estuary on the east coast of England. Catchment highlighted in grey and river channel highlighted in dark blue.

Photo 2 Lowland river drainage channels in the Great Ouse catchment which have resulted in losses of wetland and floodplain habitats.

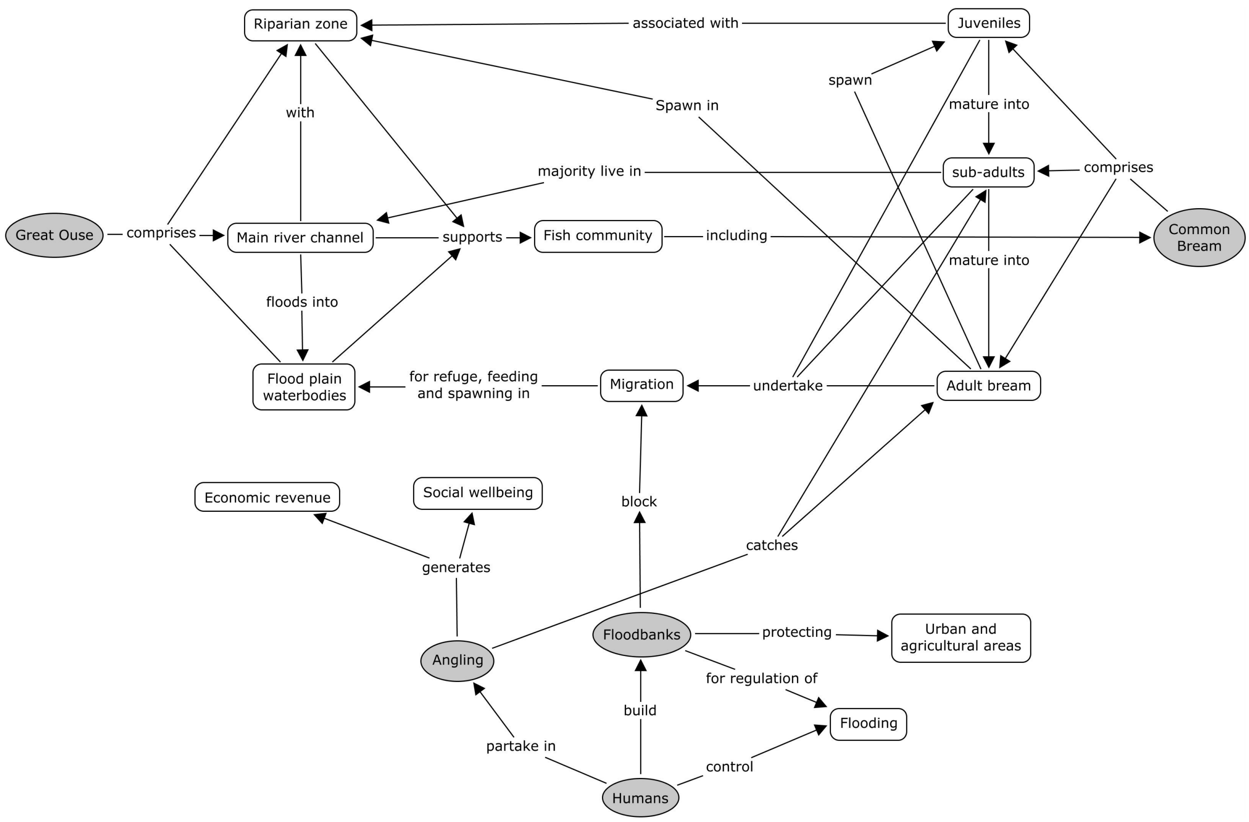

Figure 2.6 Concept map of the relationships between different life stages of a bream population and different habitats within the lowland Great Ouse.

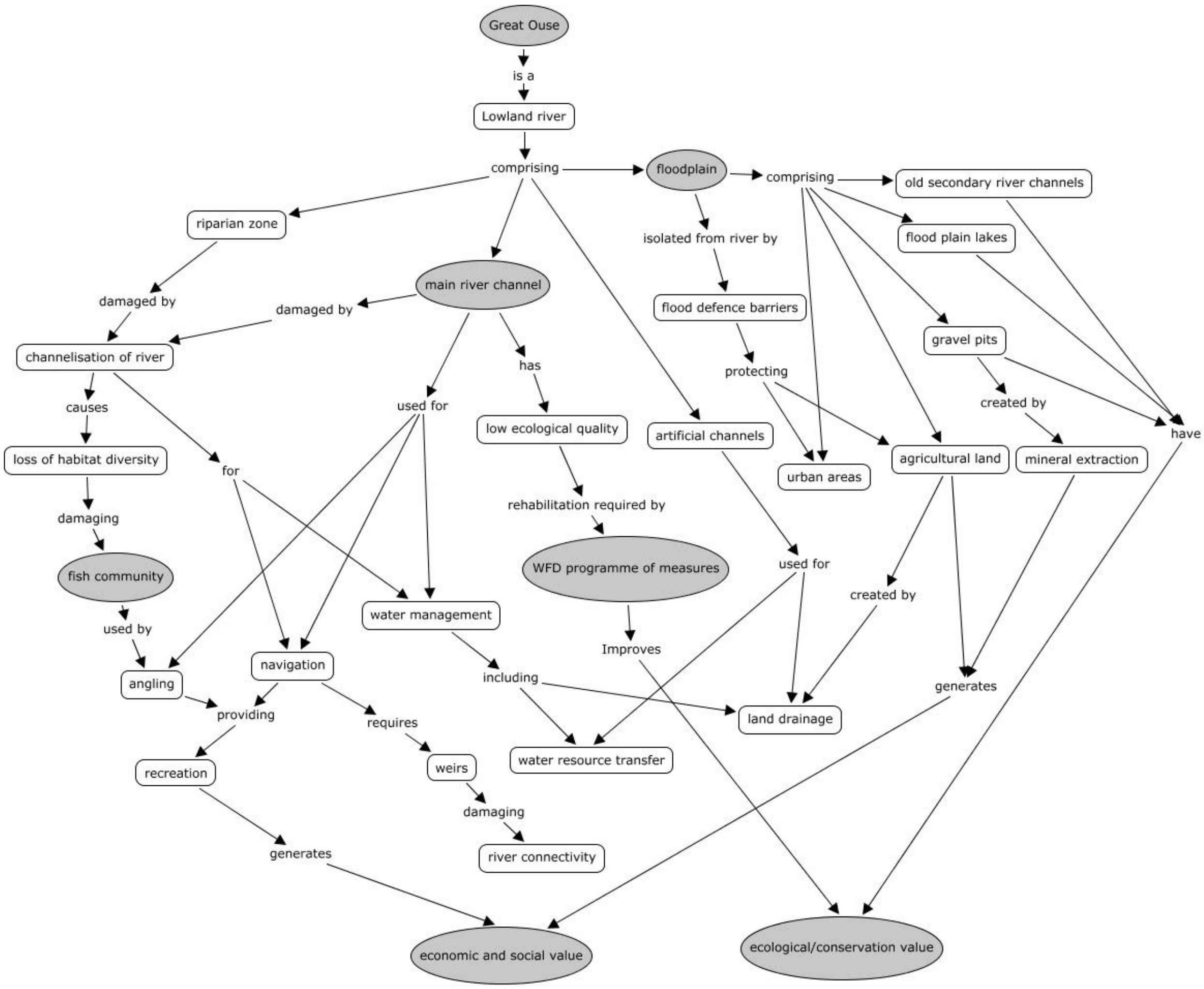

Figure 2.7 Concept map outlining the major issues regarding sustainable management of the Great Ouse lowland river system.

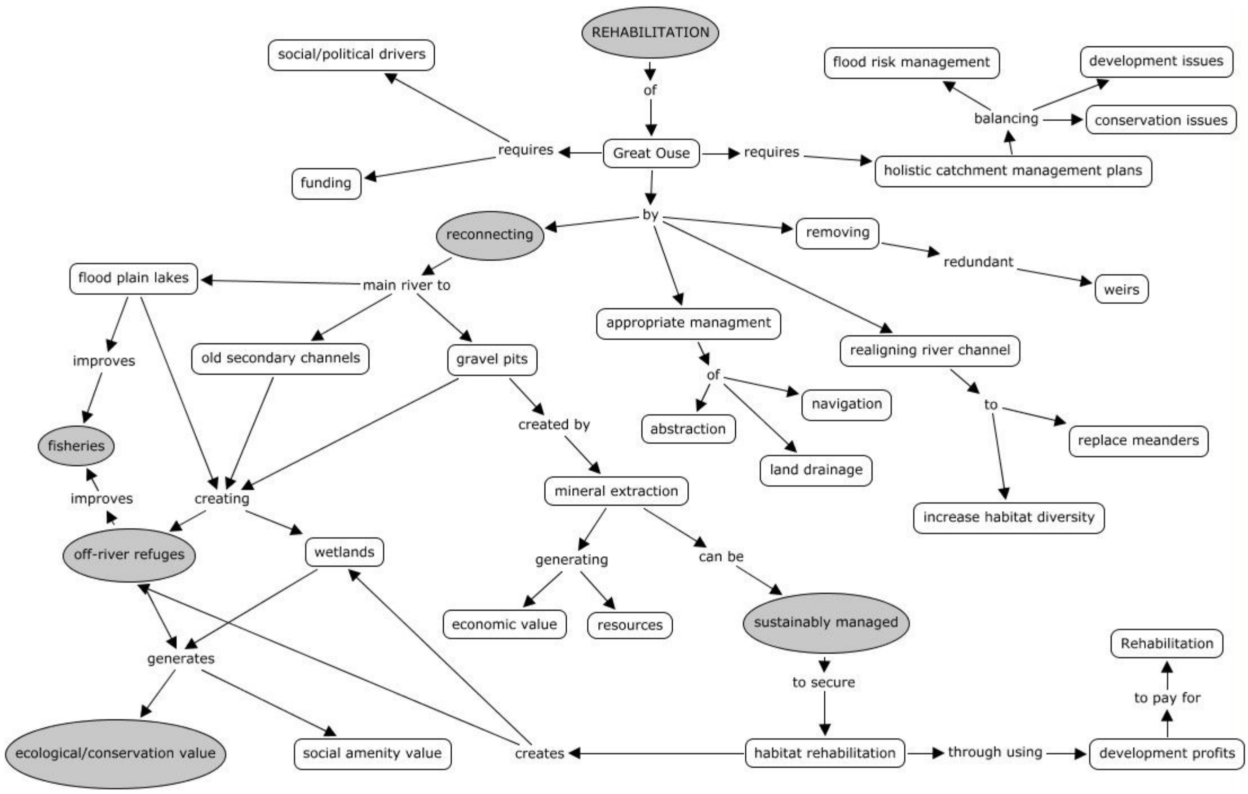

Figure 2.8 Concept map outlining the approach to rehabilitation of the Great Ouse lowland river system.

2.2.2 Specific objectives for the Great Ouse case study

The qualitative reasoning model for the Great Ouse case study should provide an educational tool that:

1. enables investigators to learn what activities are required to rehabilitate floodplain connectivity in the Great Ouse catchment and how this can link to other development activities;
2. shows an investigator the potential socio-economic benefits of re-connecting floodplain water bodies, together with the socio-economic costs and benefits of rehabilitation.

3 INITIAL SPECIFICATION OF THE RIVER TRENT AND GREAT OUSE CASE STUDIES

3.1 River Trent general system structure

3.1.1 Entities

In a broad-scale QR approach the River Trent system could be considered to have five main entities; **water**, the **river** itself, **humans**, **weirs** and **fish**. However, each of these entities can be broken down into sub-entities that have specific properties or influences in the system.

Water

Essentially within the system water can be seen as having three properties (quantities in QR); **quality**, **quantity** and **flow**; which can influence both fish populations and the other ecosystem services that can be derived from the river.

River

The river can be considered as a continuum of changing habitat types that each support different life stages of salmon and are consequently used differently by the salmon population. Additionally, the different sections of a river may provide humans with different services. In this system the river could be considered to have three subtypes; **Upland River and Tributaries** that act as spawning and nursery areas for juvenile salmon, **Lowland River** a migration corridor through which salmon smolts (life stage undergoing physiological change preparing to enter salt water) and mature adults migrate between spawning and feeding habitats, and **Estuary** the connection between the river and the open ocean where Atlantic salmon grow and mature.

Humans

Humans are the entities that make use of the river and some of the ecosystem services provided by the River Trent - deriving socio-economic gain from the river. Additionally these are the entities that can drive and undertake sustainable management and rehabilitation. Within the “human” entity a number of subtypes of human entities can be identified that are responsible for and derive benefit from a number of activities including; fishing, abstraction, waste water discharge and river regulation. Each of these activities has an economic value and contributes to current/future human well-being. The sub-types of human entity are **general population**, **environmental manager**, **stakeholder** and **anglers**.

Weirs

Weirs are present within the River Trent system as a result of historical development on the river for navigation, abstraction and hydropower generation activities. These weirs act as physical barriers to the migration of fish restricting or breaking the connectivity of salmon spawning and feeding habitats limiting or removing the ability of Atlantic salmon populations to be self-sustaining in the Trent.

Fish

Numerous subtypes of fish could be considered in a fishery based QR model of salmon rehabilitation e.g. Atlantic salmon, brown trout and coarse fish. Whilst **salmon** are the most important subtype to consider other species of fish and their associated fisheries should be considered in a full rehabilitation programme as the re-establishment of a salmon fishery could have know on effects on their fish and their fisheries. Within the salmon subtype four life stage subtypes can be considered; **juvenile**, **smolt**, **returning adults** and **spawning adult**; with each of these having different properties and requirements. Although some straying between natal rivers does occur, for salmon it generally considered that each river system has a distinct population or stock of salmon. Therefore, whilst some degree of immigration may occur, a rehabilitation model will also have to consider reintroduction (stocking).

3.1.2 Structural relations

Within the River Trent case study there are a number of processes that need to be captured as relationships between entities. Within the salmon population entities the processes include **mortality, survival/maturation** and **migration**. The relationship between the human entities and the fish population is that of **exploitation** (e.g. capture fishery) although sustainable fishery management is a form of **conservation**. The relationship between humans and the river represents both **utilisation** and **management** (including rehabilitation activities). The relationship between weirs and the river and water is that of **flow regulation** and the link between weirs and salmon is that of **obstruction** to migration.

3.1.3 External Influences

Within the River Trent case study political issues can be externalised. For example, although the WFD will be an important element of the model, the political drive behind the WFD can be seen as acting from outside of the River Trent system.

Within the concept of removals of redundant weirs (where they no longer serve their original purpose) under certain conditions there may be cultural reasons for not removing the weirs as they may be seen to have aesthetic value and potentially historical value. For example, weirs associated with providing power to some of the earliest mills built during the industrial revolution may be protected by cultural conservation orders e.g. weirs belonging to Richard Arkwright's mills on the River Derwent a major tributary of the Trent. These issues although important may not be included in the model.

Additionally, climate change and the increasing risk of frequent flooding/drought have major implications for future management of the system. However, these can be left out of the model for the purposes of looking at rehabilitation issues.

3.1.4 General modelling assumptions

The River Trent model will have to make the following assumptions to simplify the modelling process:

- The upper river and tributaries can be considered as a single unit and treated accordingly. In reality management may treat different tributaries of the Trent individually.
- Water quantity and quality in the upper river entity will directly affect the quantity and quality of water in the lower river entity. In reality the flow from a tributary in the lower river can change the quality from that flowing through the main lower river (e.g. dilution of pollution).
- The model will have to exclude the influence of estuarine and coastal conditions on the relationship between the numbers of smolts emigrating from the river and the number of mature adults returning. It will be assumed that coastal conditions and coastal exploitation of salmon are not limiting on salmon population recovery.
- The issues of land ownership and fishing rights ownership are too complicated to be included within the model so it will assume that both of these relate to society as a whole.

3.2 General system structure of the Great Ouse case study

3.2.1 Entities

In a broad-scale QR modelling approach the Great Ouse case study can be considered to have five main entities; **River**, **Water**, **Flood banks**, **Humans** and **Fish**. Each of these entities could have a number of sub-types depending on what the model focuses on.

Water

Essentially within the system water can be seen as having three properties; **quality**, **quantity** and **flow**; which can influence both fish populations and the other ecosystem services that can be derived from the river.

River

In the context of the Great Ouse system it is difficult to define the river as a single entity given that in a natural situation a lowland floodplain river is in fact a complex of permanently/periodically connected secondary channels, lakes and wetlands. However, within this model the river can be considered to represent the **Catchment**, the **main river channel**, the **riparian zone** and the **floodplain water bodies**. The catchment can be broken down into sub-types of **agricultural land**, **urban areas** and **wetlands**. The floodplain zone of a lowland river catchment is the zone that is exposed to flooding from the main river channel during periods of high flow (or would be without human intervention). Within the wetland floodplain of the Great Ouse there are a number of **floodplain water body** entities; including **back waters**, **lakes** and **gravel pits**. These are all types of floodplain water body that may be permanently or periodically connected to the main river channel. All these water bodies may provide good habitat for fish and for wider ecology. Habitats in both of these entity subtypes can be considered to have both **quality** and **quantity** properties. These properties influence the properties of the ecological entities (fish and wider biodiversity).

Flood banks

Flood banking are flood defence measures built to regulate flow and to protect urban and agricultural land from flooding. They act to disconnect the floodplain from the main river channel. This isolates lowland fish species from accessing floodplain water bodies as spawning and refuge habitats.

Humans

In the Great Ouse catchment there are a number of human activities; mineral extraction, land drainage, flood defence, navigation, agriculture and fishing. Each of these relates to number of human entity subtypes. Each of these human entity subtypes/activities influences or derives value (economic or social) from the river system and as such are all stakeholders in the management of the river. In the Great Ouse system the sub-types of human entity are; **general population**, **environment manager**, **stakeholder** and **anglers**.

Fish

Within the Water Framework Directive, river management aims to deliver good ecological status (or potential) to all surface water bodies. This requires that rivers are managed so that the ecology of the system is relatively un-impacted by human uses of rivers or at least that, where rehabilitation of an impact is impossible or the use is too important to humans, the quality of the river sustains the best possible ecology alongside maintaining the current use of the river. In the context of the WFD fish are used as one of the measures of ecological status. In a lowland river the status of the populations of some floodplain species is related to the connectivity between floodplain waters and the main river channel. This is because some species use the different habitats available at different life stages (**egg**, **juvenile**, **sub-adult** and **adult**) and for different purposes (spawning, feeding, refuge against high flows etc.). In the Great Ouse, one such species in the common **bream** (*Abramis brama* L.).

3.2.2 Structural relations

Within the Great Ouse case study there are a number of processes that need to be captured as relationships between entities. The relationship between humans and the river represents both **utilisation** and **management** (including rehabilitation activities). The relationship between the river and the floodplain is that of **flooding** and needs to reflect the concept of **connectivity** between habitats. Connectivity of habitats allows the **migration** of fishes between the habitats they require to spawn, survive and thrive within the river.

3.2.3 External Influences

Within the Great Ouse case study political issues can be externalised. For example, although the WFD will be an important element of the model, the political drive behind the WFD can be seen as acting from outside of the Great Ouse system. Furthermore, the increasing demand for water and urban development for housing can be seen as an external factor acting on the Great Ouse catchment.

Additionally, climate change and the increasing risk of frequent flooding/drought have major implications for future management of the system. However, these can be left out of the model for the purposes of looking at rehabilitation issues.

3.2.4 Assumptions

The Great Ouse case study will have to make the following assumptions to simplify the system:

- Whilst flow, abstraction and land drainage are critical issues in the management of the Great Ouse system they can externalised in a model looking at connectivity of the river to floodplain water bodies. It can be assumed that management of these things will allow development of floodplain water bodies.
- The model will assume that all types of floodplain water body will deliver the same type of benefit to the ecology of the river although the model will attempt to capture that having a diversity of features has a greater benefit.

4 GLOBAL BEHAVIOUR OF THE RIVER TRENT AND GREAT OUSE CASE STUDIES

4.1 Processes and external influences to be captured in the River Trent model

4.1.1 Salmon Life cycle processes

The model for the rehabilitation of the Atlantic salmon populations of the River Trent needs to capture life cycle processes that are integral in sustaining viable populations of fish. The processes that need to be captured are **mortality/survival**, **natality**, **migration** (within local population), **growth/maturation** and **immigration** (from neighbouring populations) (Figure 2.3). The model needs to consider different life stages of salmon populations as different human pressures affect different parts of a river and consequently may have different effects on different life stages of a migratory species.

The three key processes to capture are mortality, natality and immigration as migration and growth/maturation can be represented as mortality rates between the state variables of each life stage (e.g. the influence of a mortality rate on the relationship between sequential life stages i.e. mortality of juveniles to smolts). Therefore, there are three types of life cycle process although there will be different mortality models for different life stages.

Table 4.1 Life history processes in a salmon population

Name	Entities	Quantities	Effects	Start/stop conditions
Natality	Salmon population Upper river & tributaries Water	Natality rate Number of spawning salmon Number of eggs Water quality Habitat quality	Natality rate reflects the spawning activity within a salmon population. The natality rate is affected by the prevailing water and habitat quality (reflecting their influence on spawning success) and the numbers of adults spawning (reflecting population fecundity). The natality rate acts to increase the number of eggs deposited.	Natality is always active provided that there are spawning adults present and water/habitat quality is suitable. Natality will cease if there are no spawning adults in the population or water/habitat quality is badly degraded.
Immigration	Salmon population	Immigration rate Number of returning adult salmon	Whilst salmon do show strong homing instinct for their natal stream, some straying can occur between river catchments. Immigration from a neighbouring population can act to increase the number of returning adults in a population.	Immigration requires that there are neighbouring salmon populations and that some straying between catchments does occur - immigration may always be active but at low levels.
Mortality/survival egg to juvenile	Salmon population Upper river & tributaries Water	Mortality rate Survival rate Number of eggs Number of juveniles Water quality Habitat quality	The mortality rate between egg and juvenile stages reflects the influences of water and habitat quality on survival to smolt stage. The effect of the survival rate on the numbers of eggs and subsequent juveniles surviving captures both survival and maturation of salmon in that it increases the number of juveniles but reduces the number of eggs. A high mortality rate limits the number of juveniles that can be produced from any number of eggs.	The mortality rate is always active provided that juvenile salmon are present. The size of the mortality rate will depend upon the water and habitat quality of the upper river and tributaries. Low quality water and habitat will lead to higher mortality rates.

Mortality/survival Juvenile to smolt	Salmon population Upper river & tributaries Water	Mortality rate Survival rate Number of juveniles Number of smolts Water quality Habitat quality	The mortality rate between juvenile and smolt stages reflects the influences of water and habitat quality on survival to smolt stage. The effect on the survival rate on the numbers of juveniles and subsequent smolts surviving captures both survival and maturation of salmon in that it increases the number of smolts but reduces the number of juveniles. A high mortality rate limits the number of juveniles surviving to smolt life stages and hence reduces the numbers of smolts migrating out to sea.	The mortality rate is always active provided that juvenile salmon are present. The size of the mortality rate will depend upon the water and habitat quality of the upper river and tributaries. Low quality water and habitat will lead to higher mortality rates.
Mortality/survival smolt to returning adult	Salmon population Upper river & tributaries Lower river Estuary Water Weirs	Mortality rate Survival rate Number of smolts Number of returning adults Water quality Structure of weirs	This mortality rate acts to regulate the numbers of smolts surviving to become adults which return to the river. This mortality rate can be used to reflect impacts on the population during the downstream migration (e.g. mortality of smolts due to entrainment in abstraction / hydropower generation. In a wider model that considers estuarine and marine survival this rate could be used to also reflect these impacts.	The mortality rate is always active provided that smolts are present. The size of the mortality rate will depend upon the water quality of the river and the passability of the weirs and the numbers of smolts entrained by abstraction/hydropower generation. Low quality water will lead to higher mortality rates, especially in the lowland river.
Mortality/survival returning adult to spawning adult	Salmon population Lower river Estuary Water Weirs	Mortality rate Survival rate Number of returning adults Number of spawning adults Water quality Structure of weirs	This mortality rate acts to regulate how many of the returning adults actually migrate up into the upper river and tributaries to become spawning adults. This mortality rate is influenced by the water quality of the lower river and the passability of any weirs that may be present.	The mortality rate is always active provided that returning adult salmon are present.

4.1.2 Human activity processes

There are a number of human activities that may be modelled as processes in the system. If the model was just concerned with the salmon life cycle then each of these activities could be considered as an external influence over the salmon model. However, given that the case study objectives are for the socio-economic aspects of river rehabilitation to be captured in a QR model then these activities can be seen as integral processes. The key human activity processes that need to be captured are pollution, river regulation (for a variety of purposes e.g. abstraction, hydropower generation etc.) and salmon angling (exploitation of returning adult salmon).

Table 4.2 Human activity processes and there influence on the River Trent

Name	Entities	Quantities	Effects	Start/stop conditions
Salmon Angling	Fishery Salmon population River	Numbers of returning salmon Number of fishermen Economic value of fishery Angler satisfaction	Salmon angling is a form of exploitation - the fishing pressure, together with the numbers of returning salmon available for capture influence the number of salmon caught. In return the more salmon that are caught the more people will want to participate in salmon angling, increasing the number of anglers involved. The more anglers involved and the more fish captured acts to increase the anglers’ satisfaction in the fishery and consequently increases the economic value of the fishery.	For salmon angling to occur there must be a run off returning salmon available for capture. If the numbers of returning salmon are low, and results in low catches, then the angler satisfaction will decrease and the numbers of fishermen will decrease and as a consequence the value of the fishery will decrease until fishing no longer occurs.

Pollution - waste water discharge	Water	Water quality Pollution discharge rate	Pollution via waste water discharge (e.g. output from sewage treatment works) acts to reduce the water quality in rivers. This in turn reduces the ability of the river to sustain populations of sensitive species such as salmon. High levels of pollution can act to increase mortality rates for juvenile stages and also poor water quality can also act as a barrier to migration for adult salmon.	Presence/absence of a human population
River channelisation and impoundment	Water River Weirs Human	Presence of weirs Passability of weirs Connectivity of weirs	River regulation can have a variety of reasons (abstraction, navigation, hydropower generation etc). Weirs also act as barriers to fish migration, depending upon the structure of the weir and their passability (the passability of weirs affects the connectivity of a river)	Presence/absence of a human population

4.1.3 Rehabilitation activity processes

Rehabilitation of a salmon population in the River Trent requires a number of activities to ameliorate the impacts of human population utilisation of the river. The key aspects for rehabilitation that need to be represented are mitigation or removal of barriers (weirs), stocking of juvenile salmon, waste water treatment, appropriate management of abstraction, rehabilitation of habitat and sustainable management of fishery exploitation (e.g. catch and release).

Table 4.3 Human activity processes and there influence on the River Trent

Name	Entities	Quantities	Effects	Start/stop conditions
Stocking	Humans Salmon population	Numbers of juvenile salmon Stocking rate	Stocking is a fishery management method that acts to increase the numbers of juvenile salmon in a population in mitigation of a low natural natality rate or as compensation for exploitation of returning adults.	Fishermen perceive that stocks are lower than required to sustain the fishery through natural natality alone. Or becomes active when fishery managers try to re-introduce a species into a river.
Habitat rehabilitation	Humans River Water	Rehabilitation rate Habitat quality	Habitat rehabilitation increases the quality and quantity of habitat for juvenile salmonids, this increases the carrying capacity of the river and reduces the mortality rate of juveniles meaning that more survive to become smolts and migrate to sea.	Active when there is a political/social desire to improve the river (e.g. WFD programme of measures). Only active when there is public will/economic backing.
Waste water treatment	Humans Water	Rehabilitation rate Pollution rate Water quality	Waste water treatment reduces the amount of organic/chemical pollution that enters a river, this leads to the rivers becoming cleaner and being able to support a more diverse flora and fauna which includes sensitive species such as salmon.	Active when there is a political/social desire to improve the river (e.g. WFD programme of measures). Only active when there is public will/economic backing.
Rehabilitation of weirs	Humans River Weirs	Connectivity of river Mortality rate of returning adult salmon Number of spawning adult salmon Natality rate	Rehabilitating weirs on rivers, either by their complete removal or by-passing, increases the connectivity of rivers allowing more salmon easier access to spawning habitats thus increasing natural natality in the population (through reducing adult mortality).	Active when there is a political/social desire to improve the river (e.g. WFD programme of measures). Only active when there is public will/economic backing. Active when weirs are no longer used for their original purpose or when there is sufficient social drive to mitigate their effects.

4.2 Causal models for the River Trent case study

4.2.1 Salmon life cycle model

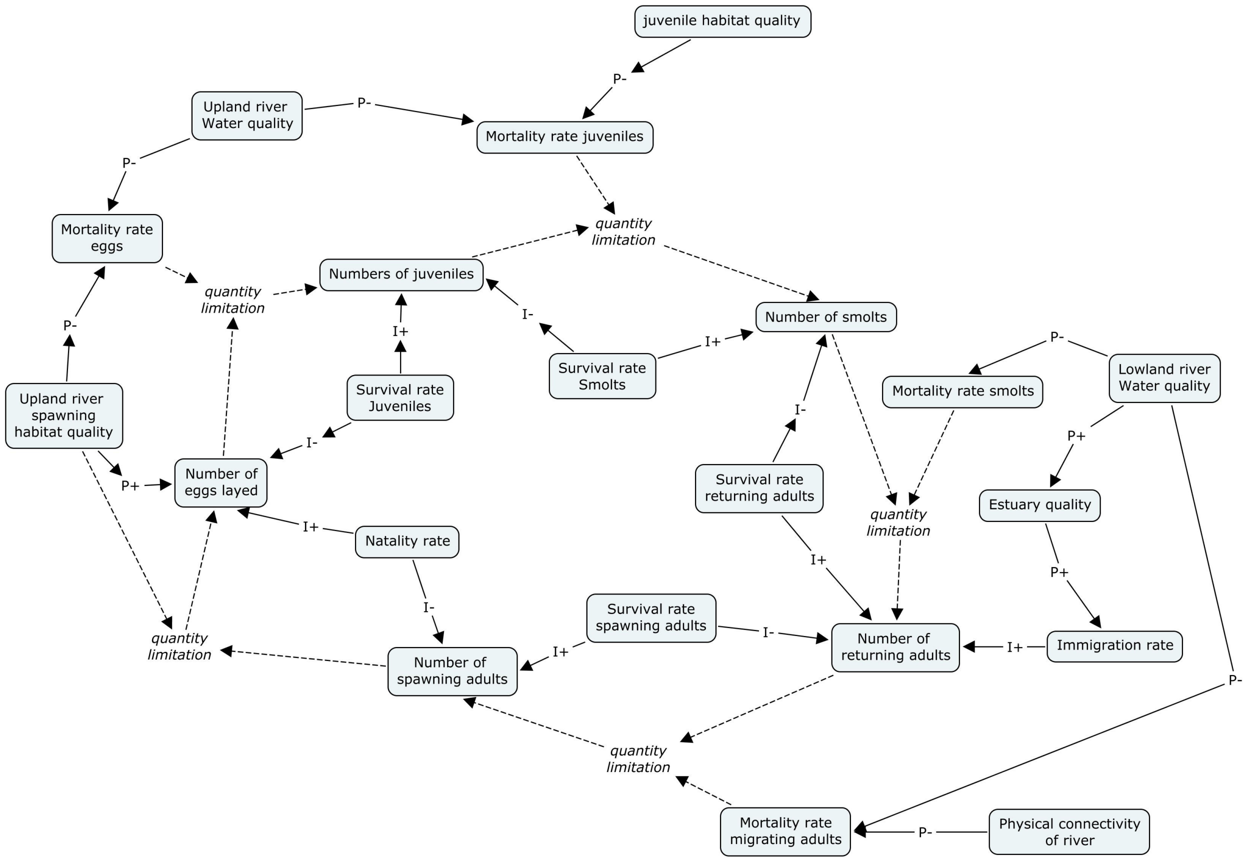

Figure 4.1 Causal model of the salmon life cycle indicating mortality and natality processes.

In the salmon life cycle model (Figure 4.1) which forms the focus of the River Trent case study the numbers of each life stage are regulated by the natality rate, survival rates and mortality rates between each life stage. In turn each survival rate acts to increase the numbers of the next life stage whilst also reducing the numbers of the previous life stage. This reflects the maturation process. The activity of the survival rate is controlled by a table of allowable values between the numbers of the previous life stage and the mortality rate of the previous life stage. In this situation the magnitude of each survival rate are equal to each other, and as such only act to increase or decrease the numbers of each life stage. The maximum numbers occurring at each life stage are regulated by the mortality rate of each life stage. This mortality rate can be seen as a proportional mortality rate, controlling how many of the numbers of the previous life stage survive to the subsequent life stage. In each of the human activities models the human activity acts to alter the mortality rates at each stage.

4.2.2 Human activities models

Fishing exploitation

In figure 4.2 the causal model for fishing exploitation of salmon on the river Trent is described. In this model the value of the fishery and the satisfaction level of anglers are proportional to the numbers of adults returning to the river. When angler satisfaction is high then this can act to increase the numbers of fishermen and also acts to increase the value of the fishery. The value of the fishery is also directly related to the number of anglers participating (e.g. more anglers spending more money on fishing). In turn the number of anglers fishing is positively related to the catch rate of the fishery. Anglers can become dissatisfied if the numbers of fish caught are low relative to the number of anglers fishing. If anglers become dissatisfied then the numbers of anglers may decrease and the value of the fishery may decline.

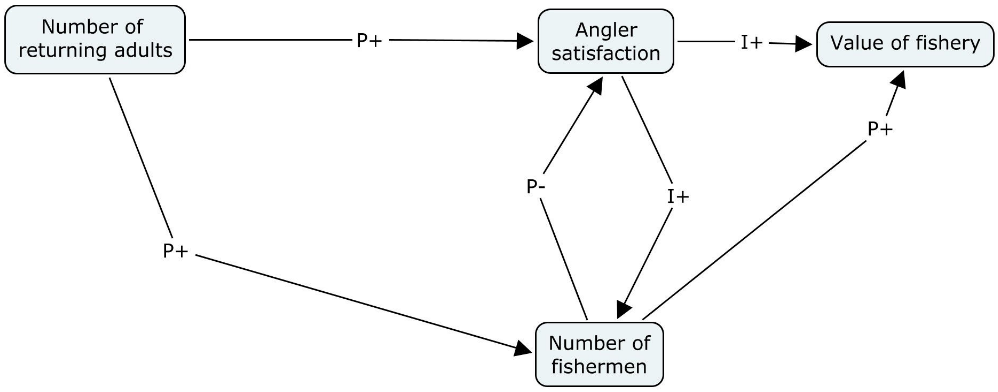

Figure 4.2 Causal model for fishing pressure on a salmon population, relating to angler satisfaction and generation of the economic value of a fishery.

Pollution and water quality rehabilitation

Pollution acts to reduce the water quality in the River Trent. The water quality can be reduced or improved by a positive or negative water quality modification rate, resulting as the difference between the pollution pressure on the system (e.g. the total amount of water pollution created by human society) and the pollution treatment level. Water quality can the go on to affect the salmon population through altering the mortality of eggs and juveniles in the upland river and by affecting the mortality rate of smolts and returning adults in the lowland river (Figure 4.3 and 4.4).

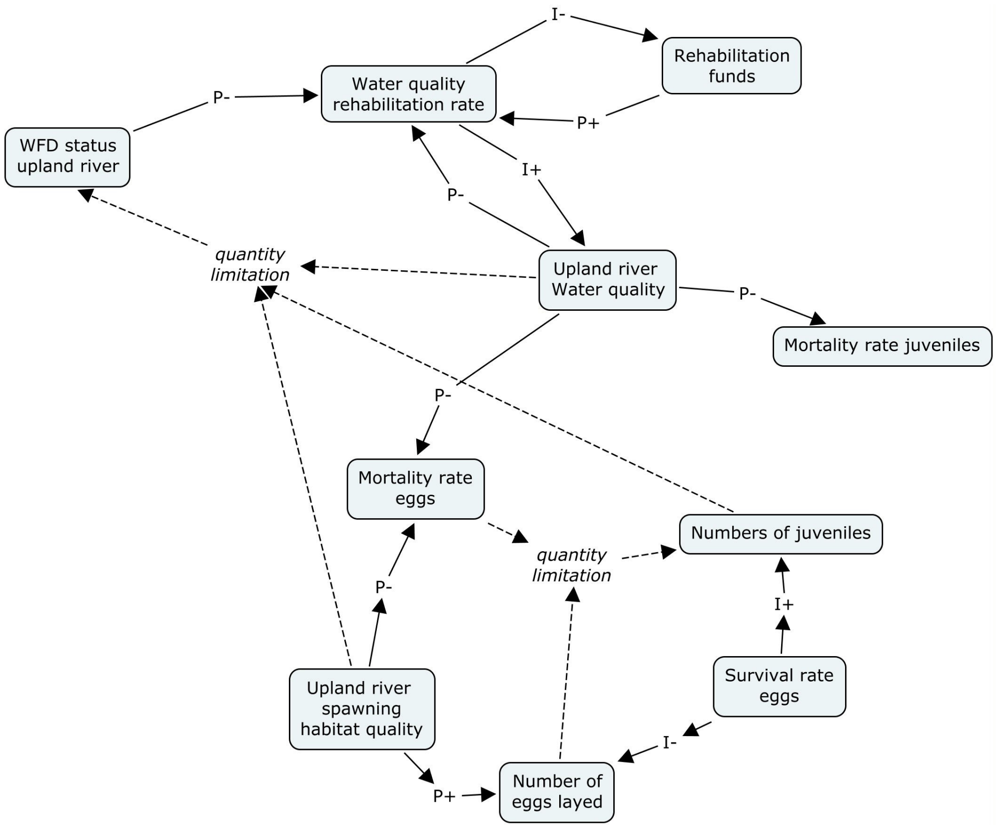

Figure 4.3 Causal model for effects of pollution on upland river water quality and the salmon life cycle processes.

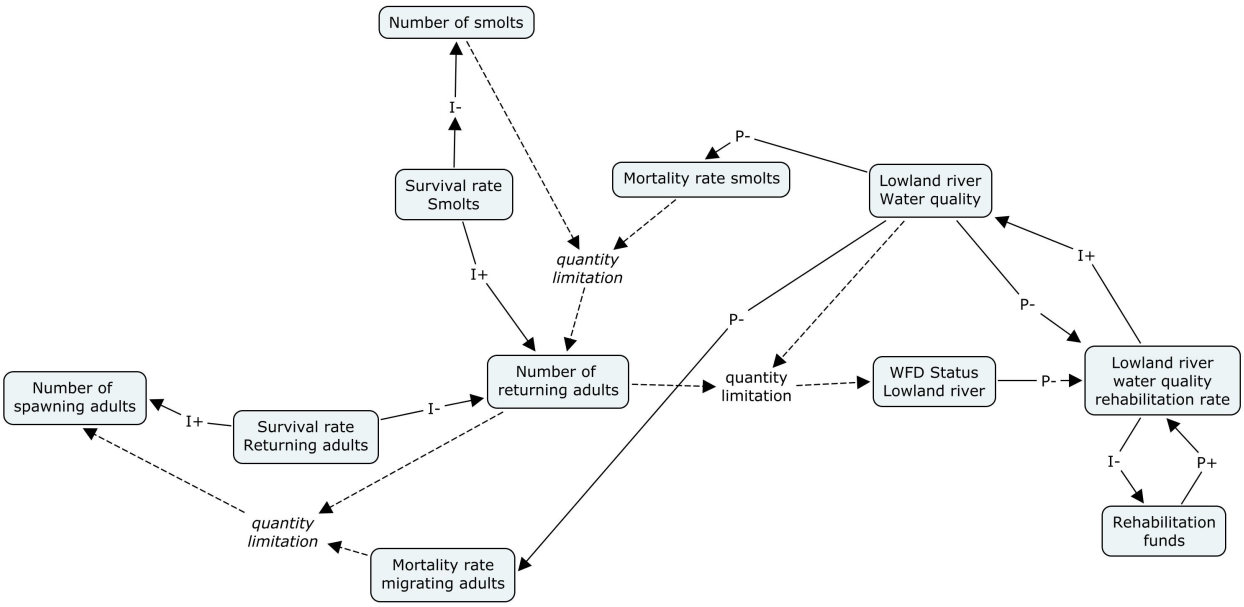

Figure 4.4 Causal model for effects of pollution on lowland river water quality and the salmon life cycle processes.

River channelisation and impoundment and rehabilitation of weirs

River channelisation and impoundment for navigation, abstraction and hydropower generation is one of the most important issues for rehabilitation of salmon populations in the River Trent. Human pressure for exploitation of water resources leads to increase in the amount of river regulation as society derives ecosystem services and economic revenue from the river. In the past the increase in the extent of regulation is reflected in the amount of weirs that are present in the river channel. The number of weirs, together with their passability (the ease or ability of fish to swim past/over the structure) affects the physical connectivity of the river. Reductions in the physical connectivity of the river can be seen as increasing the mortality rate of returning adults to the river system, reducing whether and how many adults actually can migrate through the river to reach spawning habitat in the upper river and tributaries (Figure 4.5).

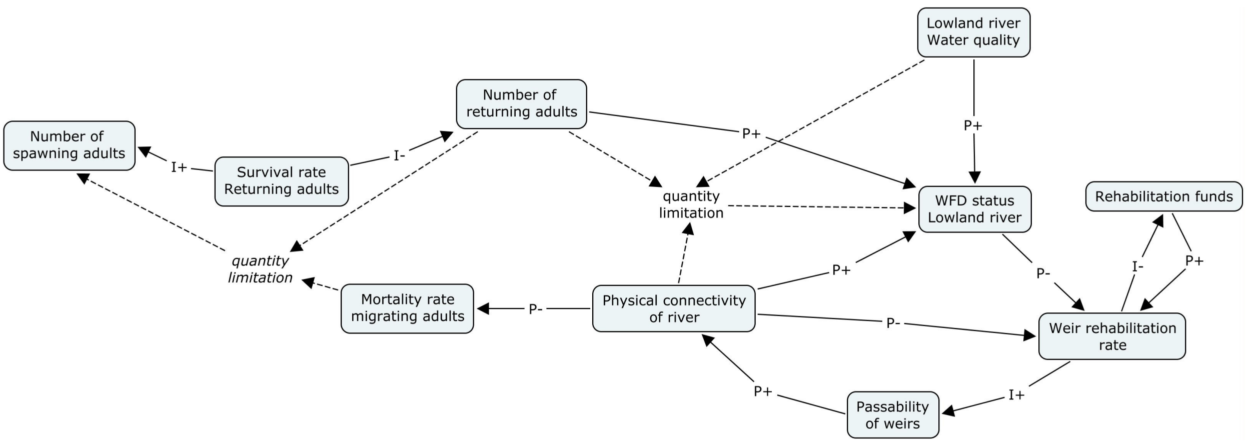

Figure 4.5 Causal model for effects of river regulation and weirs on river connectivity and the salmon life cycle processes.

Physical habitat rehabilitation

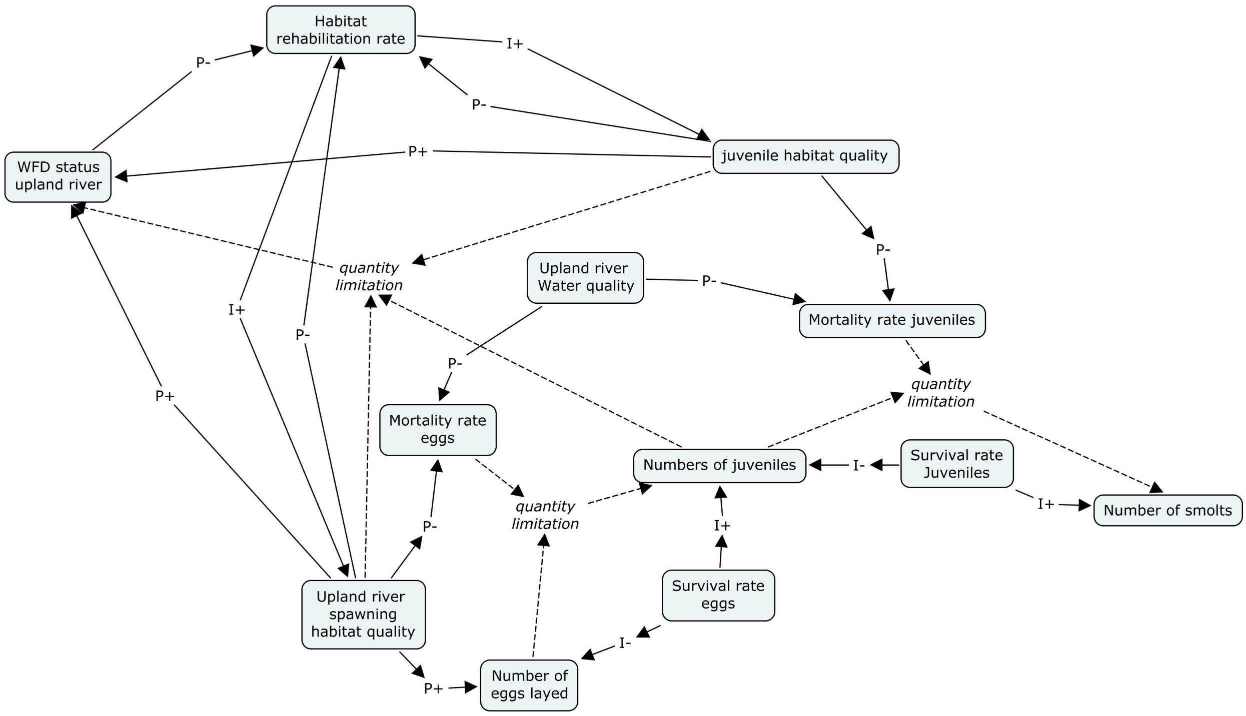

Figure 4.6 Causal model for effects of upland river habitat rehabilitation on the salmon life cycle processes.

4.3 Scenarios and behaviours for the River Trent case study

There are two main scenarios and behaviours that can be explored with this model.

1) Salmon population exists.
In this scenario the model could be set so that the habitat and water quality in the River Trent is high and the salmon population exists and is thriving and the pressure on the river from humans is low. This would reflect the state of the river prior to the industrial revolution. Then as human pressure on the River Trent increases the effects of different activities on the salmon population could be observed. For each behaviour the human activities would at first increase the mortality rate of one or more life stage which would reduce the numbers surviving to each successive life stage. The abundances of each life stage would start off high but gradually decrease until the salmon population was low or absent. Under conditions where water quality was at its lowest level and/or physical connectivity was zero then the population would be extinct.

Additionally this type of scenario can be used to explore the effects of habitat and water quality rehabilitation in a system where a salmon population is present but at low abundance and is under threat from human pressures.

2) Salmon population absent due to physical barriers to migration.
This scenario would reflect the current situation in the River Trent where water quality and habitat quality have recovered sufficiently to support salmon but the population has not regenerated due to the physical barriers preventing adults reaching spawning habitats. In this scenario the levels of each life stage would be zero and natality rate would be inactive. Under these conditions the effects of different fishery enhancement activities could be studied. The stocking rate could be activated and the effects of this management activity on the potential population recovery could be explored. It is anticipated that when physical connectivity is very low or zero that a positive stocking rate would gradually increase the numbers of juveniles, smolts and returning adults but that the number of spawning adults would not increase as the survival rate of returning adults would be very low or zero due to physical barriers to obstruction. Within this scenario the effects of removing weirs and/or improving the passability of weirs could be explored. It is anticipated that if stocking rate is active and that the connectivity of the river increases through reductions in the number of weirs and improvements in their passability then the

numbers of spawning adults will increase leading to the natural natality rate becoming active and increasing the number of juvenile salmon.

The second of these scenarios could have many variations depending upon how much rehabilitation was feasible based on socio-economic conditions and agent type factors. Additionally different scenarios could be set up with immigration rates being active or inactive and/or stocking being active/inactive.

Within this group of scenarios three particular scenarios/behaviours will be explored:

1. “Stocking only scenario” - In this scenario salmon are absent from the Trent but the environment managers and fishery stakeholders attempt to re-introduce a salmon population by stocking juvenile salmon into suitable juvenile habitats in the Upper Trent catchment. In such a situation the numbers of juveniles increases but this doesn’t correspond to establishment of a self sustaining population as management has not addressed the issue of barriers to migration of adults.
2. “Stocking plus rehabilitation of weirs” - This scenario is similar to the first except that at the same time as stocking fish as a method of re-introducing a population the environment managers and fishery stakeholders act to rehabilitate the connectivity of the river by increasing the passability of weirs through the construction of fish passes. This allows any returning adults a chance to return to spawn in the upper reaches of the river.

4.4 Processes and external influences to be captured in the Great Ouse case study

The Great Ouse case study highlights the rehabilitation issues of lowland rivers. Many of the lowland rehabilitation issues are common between the River Trent and the Great Ouse although for the Great Ouse salmon rehabilitation is not a key focus. In this situation it is rehabilitation for a diverse lowland river fish community that is important and the wider influence on local biodiversity and ecological value of the Great Ouse floodplain.

Figure 2.8 highlights the key issues in the Great Ouse system. These are land drainage, flood defence measures and river channelisation which are processes that are essentially the result of intensification of urban and agricultural areas linked to increases in human occupation/activity within the Great Ouse catchment. Historically much of the lower Great Ouse system would have been natural diverse floodplain and wetlands. Much of this has now been lost due to flood defence and channelisation measures. The floodplain is now characterised by agricultural land and the river is a complex series of semi-natural straightened/regulated channels and large artificial drainage channels.

This modification of the river channel and its floodplain has reduced the ecological status and biodiversity of the fish community in the river and the wider conservation value of the floodplain. This is because flooding processes in lowland rivers, together with the diversity of aquatic habitats (main channel, secondary channel, flood plain lakes and wetlands) and the connectivity between them are very important to sustaining abundant and diverse aquatic floral and faunal communities (e.g. fish), in turn the wider ecological value of the area has been reduced as many faunal communities (e.g. birds) rely on floodplain habitats. In this QR model the population of one lowland fish species is used to represent the ecological status and biodiversity value of the river/floodplain system. As such the life cycle processes of the common bream are related to different floodplain habitats and human activities/rehabilitation measures.

4.4.1 Fish life cycle processes

The model for the rehabilitation of the bream populations of the Great needs to capture life cycle processes that are integral in sustaining a viable population of fish. The processes that need to be captured are **mortality/survival**, **natality** and **growth/maturation** (Figure 2.6). The model needs to consider different life stages of bream populations as different human pressures affect different parts of a river and consequently may have different effects on different life stages.

The three key processes to capture are mortality, natality and survival/maturation can be represented as mortality rates between the state variables of each life stage (e.g. the influence of a mortality rate on the relationship between sequential life stages i.e. mortality of juveniles to smolts). Therefore, there are three types of life cycle process although there will be different mortality models for different life stages.

Table 4.4 Life cycle processes in a bream population.

Name	Entities	Quantities	Effects	Start/stop conditions
Natality	Bream population Lowland river Water	Natality rate Number of adult bream Number of eggs Water quality Riparian zone habitat quality	Natality rate reflects the spawning activity within a bream population. The natality rate is affected by the prevailing water and riparian habitat quality (reflecting their influence on spawning success) and the numbers of adults spawning (reflecting population fecundity). The natality rate acts to increase the number of eggs deposited.	Natality is always active provided that there are spawning adults present and water/habitat quality is suitable. Natality will cease if there are no spawning adults in the population or water/habitat quality is badly degraded.
Mortality/survival egg to juvenile	Bream population Lowland river Water	Mortality rate Survival rate Number of eggs Number of juveniles Water quality Riparian habitat quality	The mortality rate between egg and juvenile stages reflects the influences of water and habitat quality on survival to juvenile stage. The effect of the survival rate on the numbers of eggs and subsequent juveniles surviving captures both survival and maturation of bream in that it increases the number of juveniles but reduces the number of eggs. A high mortality rate limits the number of juveniles that can be produced from any number of eggs.	The mortality rate is always active provided that eggs are present. The size of the mortality rate will depend upon the water and habitat quality of the lowland river. Low quality water and habitat quality will lead to higher mortality rates.
Mortality/survival Juvenile to sub-adult	Bream population Lowland river Floodplain water bodies Water	Mortality rate Survival rate Number of juveniles Number of sub-adults Water quality Abundance of floodplain waterbodies Connectivity with floodplain	The mortality rate between juvenile and sub-adult stages reflects the influences of water and off-channel habitat quality/availability on survival to the sub-adult stage. The effect on the survival rate on the numbers of juveniles and subsequent sub-adults surviving captures both survival and maturation of bream in that it increases the number of sub-adults but reduces the number of juveniles. A high mortality rate limits the number of juveniles surviving to sub-adult life stages. Mortality is linked to the availability of off-channel habitats, these habitats can act as refuge against high flow events.	The mortality rate is always active provided that juvenile bream are present. The size of the mortality rate will depend upon the water and habitat quality lowland and its floodplain. Low quality water and habitat will lead to higher mortality rates.
Mortality/survival Sub-adult to adult	Bream population Lowland river Flood plain water bodies Connectivity to floodplain Water Flood banks	Mortality rate Survival rate Number of sub-adults Number of adults Water quality Extent of flood banking	This mortality rate acts to regulate the numbers of sub-adults surviving to become adults that inhabit flood plain water bodies and the main river. This mortality rate can be used to reflect impacts of flood banking on the connectivity between the main river and off-channel habitats. In general sub-adult bream inhabit the main river channel whereas a large proportion of adult bream will inhabit the connected floodplain water bodies.	The mortality rate is always active provided that sub adults are present. The size of the mortality rate will depend upon the water quality of the river and the habitat quality of the main river channel. The number of adults in the population will be limited by the availability of flood plain water bodies (a combination of their abundance and their connectivity with the main river channel).

4.4.2 Human activity processes

There are a number of human activities that may either be modelled as processes in the system. If the model were just concerned with the bream life cycle then each of these activities could be considered as an external influence over the bream model. However, given that the case study objectives are for the socio-economic aspects of river rehabilitation to be captured in a QR model then these activities can be seen as integral processes. The key human activity processes that need to be captured are pollution, river channelisation and impoundment (for a variety of purposes e.g. flood defence, land drainage etc.) and angling (exploitation of lowland fish community) (Figure 2.7).

Rehabilitation of the lowland Great Ouse floodplain requires a number of activities to ameliorate the impacts of human population utilisation of the river. The key aspects for rehabilitation that need to be represented are mitigation or removal of barriers (flood banks), waste water treatment, creation of floodplain waterbodies (e.g. rehabilitation of gravel pits) and rehabilitation of channel and riparian habitat (Figure 2.8). These processes are described in Table 4.5.

Table 4.5 Rehabilitation processes in the Great Ouse catchment

Name	Entities	Quantities	Effects	Start/stop conditions
Rehabilitation of channel habitat	Humans River Fish	WFD status River channel habitat quality River channel habitat rehabilitation rate Rehabilitation funds Mortality rate sub-adults Number of adults	Rehabilitation of the main river channel to improve habitat quality and diversity through creation of in-stream habitat or by realigning the river to create menders acts to reduce the mortality rate of the sub-adults. This means that more bream survive to become adults. The rehabilitation activity will also use up the funds that are available for rehabilitation. As the quality of habitat improves and the bream population increases in size so the biodiversity value and WFD status improves.	Rehabilitation of the main channel will occur if the WFD status is less that good and it is the quality of the main channel that is causing the WFD status to be poor. Rehabilitation can only occur if there are funds available. Rehabilitation will stop when funds have run out or the WFD status returns to good or better.
Rehabilitation of riparian zone habitat	Humans River Fish	WFD status Riparian habitat quality Riparian habitat rehabilitation rate Rehabilitation funds Mortality rate eggs Number of juveniles Number of eggs	Rehabilitation of the riparian zone to improve habitat quality and diversity acts to improve spawning habitat and reduce the mortality rate eggs by providing good habitat for newly hatched larval bream. This means that more bream survive to become juveniles. The rehabilitation activity will also use up the funds that are available for rehabilitation. As the quality of habitat improves and the bream population increases in size so the biodiversity value and WFD status improves.	Rehabilitation of the riparian zone will occur if the WFD status is less that good and it is the quality of the riparian zone that is causing the WFD status to be poor. Rehabilitation can only occur if there are funds available. Rehabilitation will stop when funds have run out or the WFD status returns to good or better.
Reconnection of backwaters	Humans River Fish Flood banks	WFD status River connectivity Extent of flood banking Rehabilitation funds Mortality rate sub-adults Number of adults	Reconnection of back waters acts to increase the amount of habitat available for adult bream to live in and for juveniles to seek refuge in during high flow events. Increasing the availability of connected floodplain waterbodies acts to reduce the mortality rate of juveniles allowing more to survive to sub-adult stages. The rehabilitation activity will also use up the funds that are available for rehabilitation. As the availability of connected	Reconnection of backwaters will occur if the WFD status is less than good and it is the availability of connected floodplain waterbodies that is causing the WFD status to be poor. Rehabilitation can only occur if there are funds available. Rehabilitation of flood banks can only occur if

			waterbodies increases and the bream population increases in size so the biodiversity value and WFD status improves.	it is not restricted by the amount of urban land (i.e. flood defences must be retained). Rehabilitation will stop when funds have run out or the WFD status returns to good or better.
Water quality rehabilitation	Humans River Fish Water	WFD status River water quality Water quality rehabilitation rate Rehabilitation funds Mortality rate eggs Mortality rate juveniles	Poor water quality can affect the mortality of eggs and juvenile bream. Rehabilitation of the water quality will act to reduce these mortality rates and increase the population size of bream. The rehabilitation activity will also use up the funds that are available for rehabilitation. As the water quality improves and the bream population increases in size so the biodiversity value and WFD status improves.	Rehabilitation of the water quality will occur if the WFD status is less that good and it is the water quality that is causing the WFD status to be poor. Rehabilitation can only occur if there are funds available. Rehabilitation will stop when funds have run out or the WFD status returns to good or better.
Creation of gravel pits	Humans River Floodplain	Abundance of floodplain waterbodies Gravel pit creation rate Rehabilitation funds River utilisation value Biodiversity value	Extraction of gravel from the land around the Great Ouse river is and important industry and contributes to local and national economy. In general one gravel has been extracted the pits fill with water and become artificial flood plain water bodies. These gravel pits if rehabilitated correctly can provide a biodiversity function to the catchment. If these pits are connected to the main river they can act as semi-natural off channel refuges for bream.	Creation of gravel pits will occur as long as there is demand for gravel and there is gravel available for extraction within the catchment.
Angling	Humans Fish	Number of anglers Number of adult bream Number of sub-adult bream Value of fishery Angler satisfaction	Angling is a form of exploitation although in lowland rivers all this is on a catch and release basis. The more anglers involved and the more fish captured acts to increase the anglers' satisfaction in the fishery and consequently increases the economic value of the fishery.	For bream angling to occur there must be a suitably sized population of sub-adult and adult bream available for capture. If the numbers of bream are low, and results in low catches, then the angler satisfaction will decrease and the numbers of fishermen will decrease and as a consequence the value of the fishery will decrease until fishing no longer occurs.

4.5 Causal models for the Great Ouse case study

Bream life cycle

In the bream life cycle model (Figure 4.7) which forms the focus of the Great Ouse case study the numbers of each life stage are regulated by the natality rate, survival rates and mortality rates between each life stage. In turn each survival rate acts to increase the numbers of the next life stage whilst also reducing the numbers of the previous life stage. This reflects the maturation process. The activity of the survival rate is controlled by a table of allowable values between the numbers of the previous life stage and the mortality rate of the previous life stage. In this situation the magnitude of each survival rate are equal to each other, and as such only act to increase or decrease the numbers of each life stage. The maximum numbers occurring at each life stage are regulated by the mortality rate of each life stage. This mortality rate can be seen as a proportional mortality rate, controlling how many of the numbers of the previous life stage survive to the subsequent life stage. In each of the human activities models the human activity acts to alter the mortality rates at each stage. In particular the availability of off-channel habitats (floodplain water bodies) is related to setting carrying capacities for the adult bream and also setting mortality rates for the juveniles which use these habitats as refuges against high flow events.

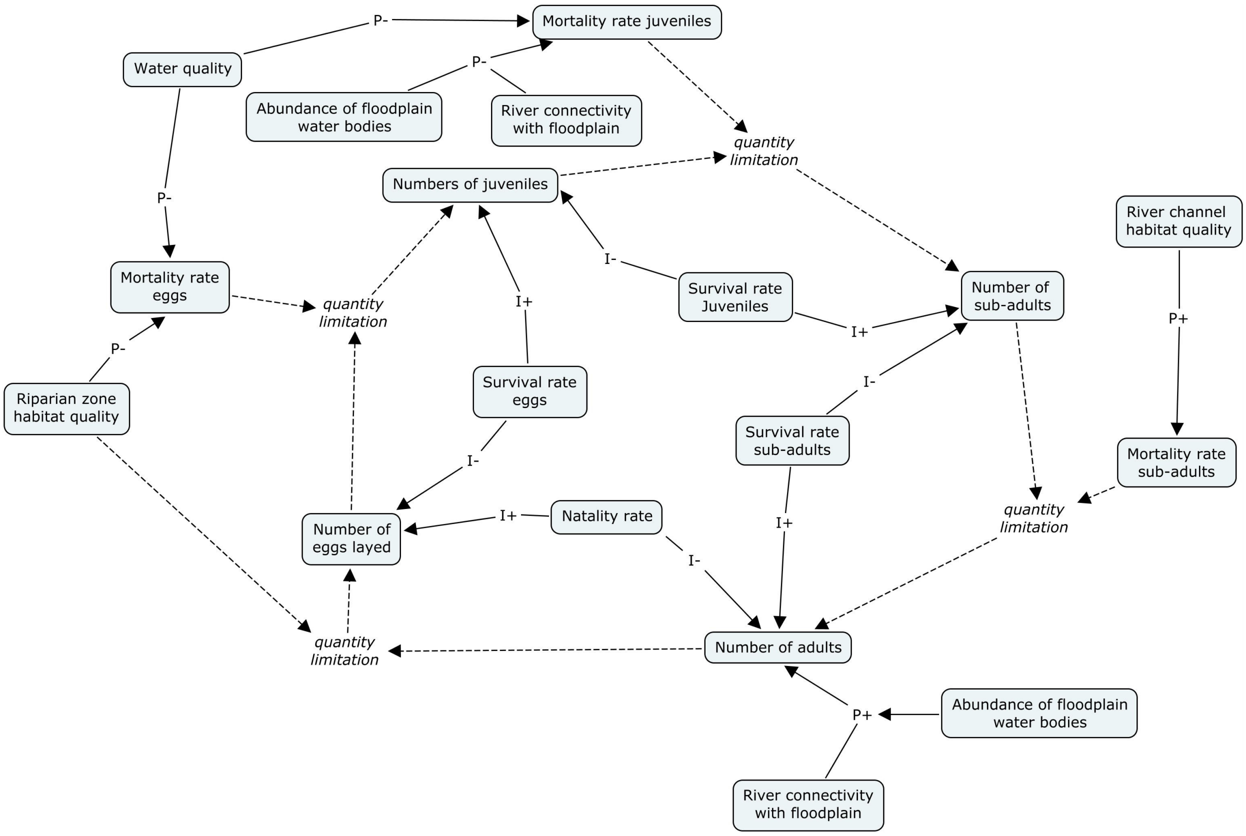

Figure 4.7 Causal model for the bream life cycle which relates to lowland river rehabilitation in the Great Ouse catchment.

The causal models for rehabilitation processes in the Great Ouse have a common structure in that the rehabilitation rate is controlled by a negative proportionality from the WFD status quantity. The WFD status quantity is itself set by a combination of positive proportionalities from a feature of the bream population (e.g. number of adults) and a measure of the environmental quality (e.g. quality of riparian habitat). This relationship sets the WFD status which in turns determines if the rehabilitation rate becomes active (WFD status declining and/or less than "good"). The activity of the rehabilitation rate also depends on a negative proportionality with the quantity that it itself positively influences. The negative proportionality together with a value limitation allows the rate to only be activated when it is the quality variable in question (e.g. channel habitat quality) that is causing the WFD status to decline of be less than "good". Additionally the rehabilitation rate has a negative influence of the amount of funds available for rehabilitation (Figures 4.8 to 4.11).

Rehabilitation of connectivity of main river channel with floodplain waterbodies

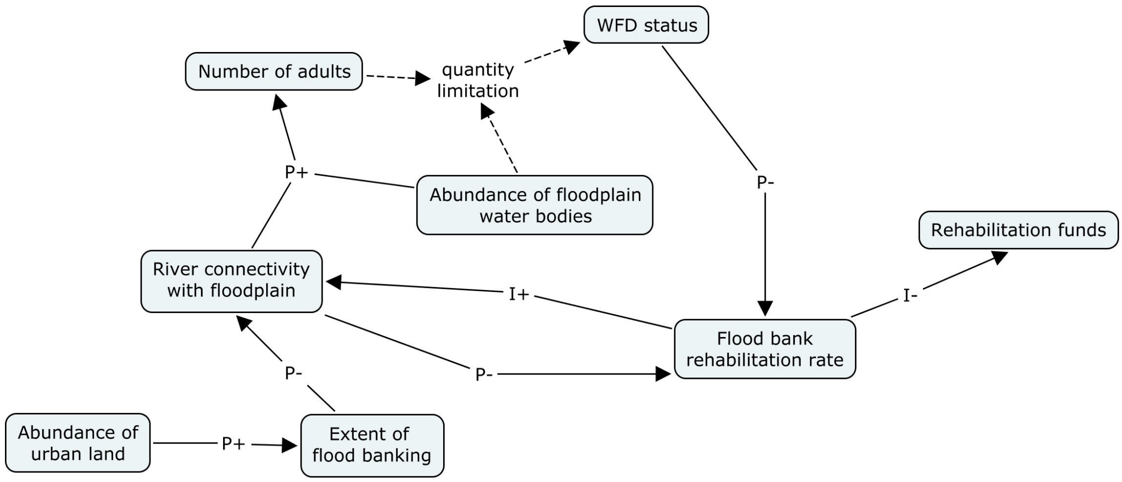

Figure 4.8 Causal model which relates lowland river rehabilitation of connectivity in the Great Ouse catchment to the bream life cycle.

Creation of floodplain waterbodies by gravel extraction

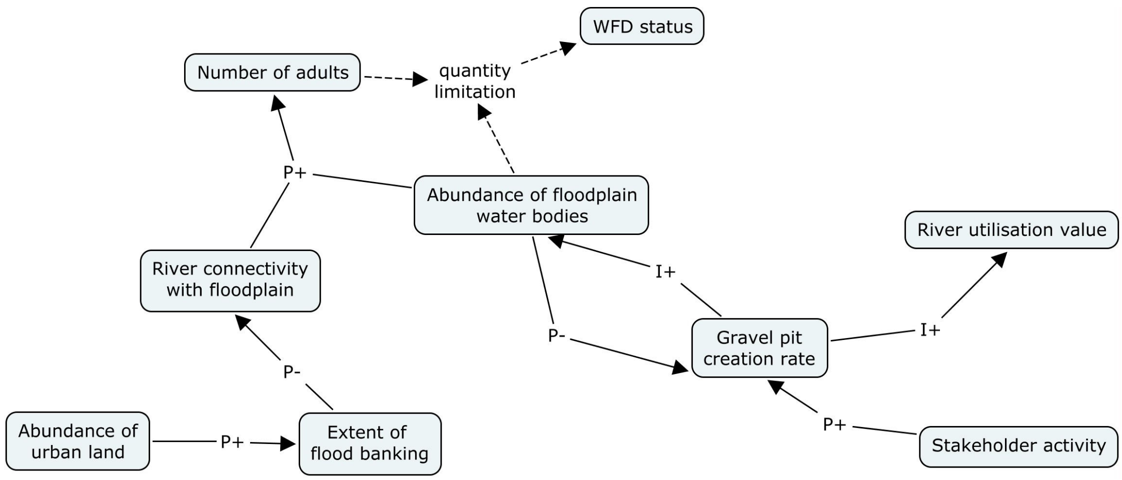

Figure 4.9 Causal model which relates gravel pit creation in the Great Ouse catchment to the bream life cycle.

Rehabilitation of riparian habitats

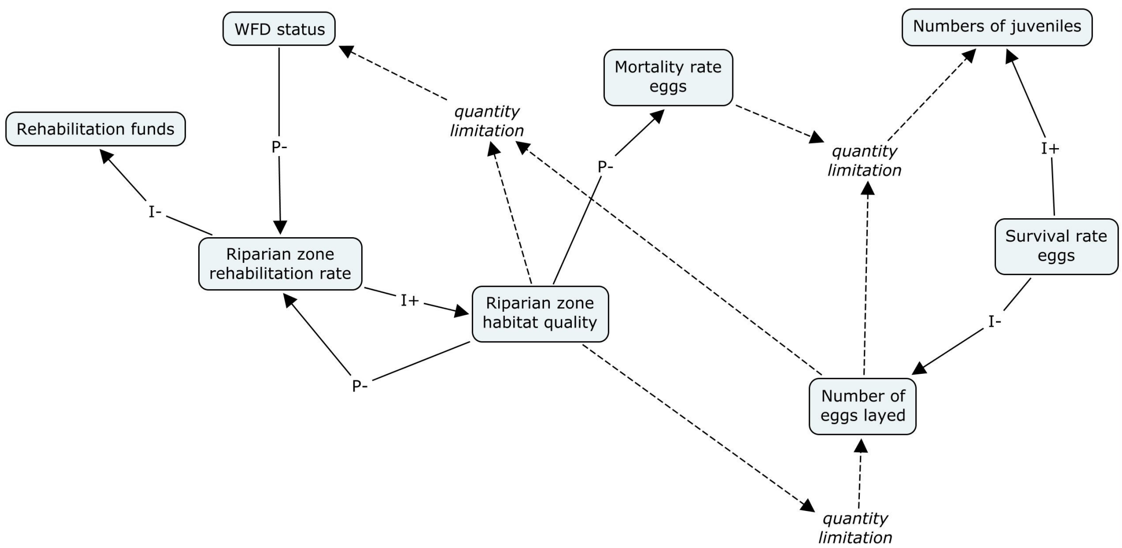

Figure 4.10 Causal model which relates rehabilitation of riparian habitats in the Great Ouse catchment to the bream life cycle.

Water quality rehabilitation

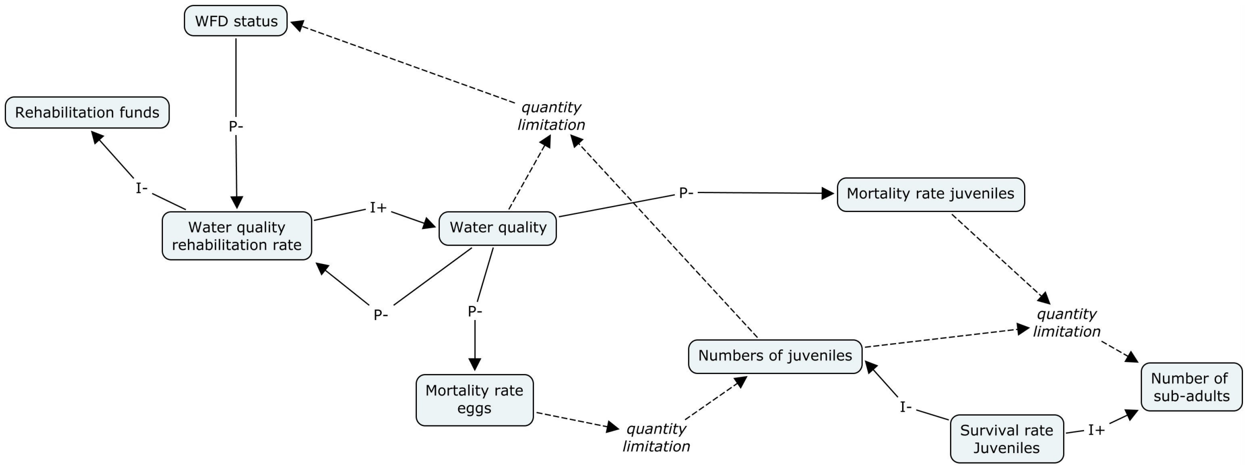

Figure 4.11 Causal model which relates rehabilitation of water quality in the Great Ouse catchment to the bream life cycle.

Angling

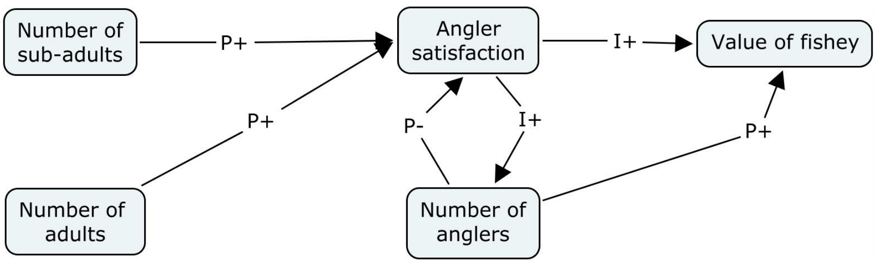

Figure 4.12 Causal model which angling in the Great Ouse catchment to the bream life cycle.

4.6 General scenarios and behaviours for the Great Ouse case study

Within the Great Ouse study the key scenario and behaviour to study is the change from the current situation where the river is highly channelised and isolated from its floodplain with low biodiversity and ecological value to a situation where rehabilitation activity has re-established floodplain connections and improved the ecological status of the river. This scenario basically follows the objectives of the WFD which aims to maintain good ecological status in all surface waterbodies. However, given the considerations of human pressures on the Great Ouse system and the extent of modification in the system the ecological status that can be attained through rehabilitation activities will be limited to what can be achieved in the context of continued human usage of the catchment.

5 DETAILED SYSTEM STRUCTURE FOR THE RIVER TRENT CASE STUDY: ENTITIES, ATTRIBUTES AND CONFIGURATIONS

5.1 Detailed system structure

The entities and entity structure represented here summarises the key concepts and their relationships presented in the previous sections.

5.1.1 Entities overview

- Human
    - General Population
    - Environment manager
    - Stakeholder
    - Anglers
- River
    - Catchment
    - Upland river
        - Spawning habitats
        - Juvenile habitats
    - Lowland river
    - Water
- Fish
    - Salmon
        - Egg
        - Juvenile
        - Smolt
        - Returning adult
        - Spawning adult
- Weirs

5.1.2 Configurations overview

There are a number of configurations that relate these entities to each other. The key configurations, in addition to standard configurations such as “is a”, are:

- “inhabits” e.g. salmon inhabit the river
- “migrate through” e.g. returning adult salmon migrate through the lowland river
- “matures into” e.g. juvenile salmon mature into smolts
- “occupies” e.g. humans occupy the river catchment
- “utilise” e.g. humans utilise water
- “rehabilitate” e.g. environment manager rehabilitates river habitats
- “exploits” e.g. anglers exploit the adult salmon

5.2 Agents

Within the River Trent system the European Water Framework Directive can be seen as an Agent which affects the approach to management of the river and rehabilitation activities that might occur. The WFD provides a driver for change and for sustainable river utilisation/management.

5.3 Assumptions

Within the model there needs to be a number of assumptions to reflect what is known about salmon survival and recruitment.

- The numbers of any life stage of salmon are increased by recruitment from the previous life stage ("matures into"), are limited by the actual numbers of the previous life stage and will reduce due to maturation to the next stage and mortality acting on the life stage.
- The numbers of any life stage are limited by the availability of suitable habitats (e.g. habitat quality); this represents the carrying capacity concept. For example the number of juveniles may be limited by the quality of the upland river juvenile habitats.
- The survival/maturation rate is a z,p rate that has an I+ influence on the following life stage and an I- influence on the preceding life stage. It is always active unless the number of the preceding life stage is zero. The I- influence on the preceding life stage reflects maturation i.e. the reduction in the numbers of life stage x as they mature into x+1. The "plus" value of all the survival/maturation rates is equal.
- The numbers at each life stage are limited by a table of allowable values (value correspondences) between mortality rates and the numbers of life stage x-1.
- Issues regarding marine survival are ignored within the model.
- Human pressures and/or rehabilitation activities affect the salmon population by acting on the habitat (carrying capacity) and/or on directly on the mortality process between life stages.

5.4 Quantities and quantity spaces

State variables

- **Water**
  - Water quality - the quality of water in the river affects the survival of salmon
  - Water quantity - water quantity reflects water flow which affects habitat quality and availability
- **Salmon**
  - Number of eggs
  - Number of juveniles
  - Number of smolts
  - Number of returning adults
  - Number of spawning adults
- **River**
  - Upland river habitat quality
  - River connectivity
  - WFD status
- **Human**
  - Number of anglers
  - Human pressure on system
  - Value of fishery
  - Angler satisfaction
  - River utilisation value
  - Rehabilitation funds available
- **Weirs**
  - Weirs present
  - Passability of weirs

Rate variables

- **Salmon**
  - Mortality rate (egg to juvenile)
  - Mortality rate (juvenile to smolt)
  - Mortality rate (smolt to returning adult)
  - Mortality rate (returning adult to spawning adult)
  - Natality rate (spawning adult to eggs)
  - Maturation/survival rate (egg to juvenile)
  - Maturation/survival rate (juvenile to smolt)
  - Maturation/survival rate (smolt to returning adult)
  - Maturation/survival rate (returning adult to spawning adult)
  - Immigration rate
- **Human**
  - Weir rehabilitation rate
  - Habitat rehabilitation rate
  - Water quality treatment rate
  - Stocking rate (rate of stocking with juveniles)

Table 5.1 Quantities and quantity spaces in the River Trent salmon rehabilitation QR model

Type	Quantity	Quantity space
State		
	Water quality	Bad, poor, moderate, good, high
	Water quantity	Very low, low, medium, high, natural
	Number of eggs	Zero, v low, low, med, abundant, v abundant, high
	Number of juveniles	Zero, v low, low, med, abundant, v abundant, high
	Number of smolts	Zero, v low, low, med, abundant, v abundant, high
	Number of returning adults	Zero, v low, low, med, abundant, v abundant, high
	Number of spawning adults	Zero, v low, low, med, abundant, v abundant, high
	Upland river habitat quality	Bad, poor, moderate, good, high
	River connectivity	Zero, restricted, unrestricted
	WFD status	Bad, Poor, Moderate, Good, High
	Number of anglers	Zero, low medium, high
	Human pressure on system	Zero, low medium, high
	Value of fishery	Zero, low, medium, high
	Angler satisfaction	Unsatisfied, satisfied
	River utilisation value	Zero, low, medium, high
	Rehabilitation funds available	Zero, low, medium, high
	Weirs present	Zero, present
	Passability of weirs	Zero, low, medium, high, max
Rate		
	Mortality rate (egg to juvenile)	Natural, low, medium, high
	Mortality rate (juvenile to smolt)	Natural, low, medium, high
	Mortality rate (smolt to returning adult)	Natural, low, medium, high
	Mortality rate (returning adult to spawning adult)	Natural, low, medium, high
	Natality rate (spawning adult to eggs)	Zero, plus
	Maturation/survival rate (egg to juvenile)	Zero, plus
	Maturation/survival rate (juvenile to smolt)	Zero, plus
	Maturation/survival rate (smolt to returning adult)	Zero, plus
	Maturation/survival rate (returning adult to spawning adult)	Zero, plus
	Immigration rate	Zero, plus
	Weir rehabilitation rate	Zero, plus
	Habitat rehabilitation rate	Zero, plus
	Water quality treatment rate	Zero, plus
	Stocking rate	Zero, low, medium, intensive

5.5 Scenarios and behaviours

The salmon life cycle rehabilitation model could be used to explore a range of scenarios with different starting points to understand the effects of different types of rehabilitation. In most cases the starting point would be the natural situation where salmon do not have a self sustaining population in the River Trent. Each rehabilitation activity (stocking, habitat improvement, water management, and weir removal/fish pass construction) can then be explored either as individual processes or as combinations.

5.5.1 Stocking only scenario

In this scenario stocking juveniles occurs whilst funding is available. The scenario assumes that even though the number of returning adults increases that the numbers of fish caught by the fishery are low as zero connectivity means the adults cannot enter the river system. Therefore, as stocking continues the funds are used up and not replenished by revenue from the fishery.

Table 5.2 states in the "stocking only scenario

State	Values and (in)equality	Description
1	Salmon population absent, anglers are dissatisfied, stocking rate is plus, rehabilitation funds are available, connectivity of river is zero.	The stocking process acts to increase the number of juveniles, stocking is active and funds are available for rehabilitation and stocking occurs because anglers are dissatisfied with the fishery
2	Number of juveniles low and increasing, stocking active	Stocking is still active, funds are decreasing because they are being used up.
3	Number of juveniles and smolts increasing to levels limited by mortality and habitat value correspondences	Juveniles start to mature into smolts and start to emigrate from the river. Stocking is still active but funds are still reducing.
4	Number of juveniles and smolts reach limits fixed by mortality and habitat conditions, number of returning adults starts to increase, connectivity is zero	Smolts start to mature and return as adults to the river, connectivity is still zero so no adults become spawning adults. Funding for stocking is declining because no revenue is being generated by the fishery due to a lack of adults migrating through the river.
5	Stocking stops due to lack of funding caused by the lack of adults reaching spawning grounds. Numbers of juveniles no longer increasing	Funds for stocking have run out due to lack of revenue from the fishery.
6	Numbers of juveniles, smolts and returning adults decreasing due to maturation and mortality	A lack of stocking and spawning adults means that the population starts to decline again.
7	Salmon population absent, stocking rate zero, no funds available for rehabilitation, connectivity is zero	The lack of stocking and absence of a self-sustaining salmon population. WFD status is still poor or bad.

5.5.2 Stocking and rehabilitation of weirs scenario

In this scenario stocking juveniles occurs whilst funding is available and the connectivity is improved by construction of passes on the weirs present. The scenario assumes that even though the number of returning adults increases that the numbers of fish caught by the fishery are low as zero connectivity means the adults cannot enter the river system. Therefore, as stocking continues the funds are used up and not replenished by revenue from the fishery.

Table 5.3 states in the "stocking and rehabilitation of weirs" scenario

State	Values and (in)equality	Description
1	Salmon population absent, stocking rate is plus, rehabilitation funds are available, connectivity of river is zero but weir rehabilitation rate is plus	The stocking process acts to increase the number of juveniles, stocking is active and funds are available for rehabilitation, rehabilitation of the weirs acts to increase connectivity of the river
2	Number of juveniles low and increasing, stocking active, connectivity of river improving	Stocking is still active, funds are decreasing because they are being used up.
3	Number of juveniles and smolts increasing to levels limited by mortality and habitat value correspondences	Juveniles start to mature into smolts and start to emigrate from the river. Stocking is still active but funds are still reducing.
4	Number of juveniles and smolts reach limits fixed by mortality and habitat conditions, number of returning adults starts to increase, connectivity is fixed by value correspondences	Smolts start to mature and return as adults to the river, connectivity is still restricted but some adults become spawning adults - this means some fish are available to anglers to catch which starts to generate fishery revenue.

	at "restricted"	
5	Number of spawning adults increases and natality process becomes active	The presence of spawning adults starts the natality process and recruitment occurs within the limits set by habitat and water quality conditions - a self sustaining population is present. .
6	Numbers of juveniles, smolts and returning adults increasing due to stocking and natality	The presence of self sustaining population means stocking is no longer active. Fishery revenue and number of anglers increases provided numbers of returning/spawning adults are sufficient.
7	Salmon population present, stocking rate zero, , connectivity is restricted	A sustainable fishery is present - WFD status > moderate

5.5.3 Habitat rehabilitation

In this scenario a population is present but the numbers are limited by low habitat quality for spawning and juveniles. Habitat rehabilitation acts to increase the carrying capacity of the system and reduce mortality levels.

Table 5.4 states in the "habitat rehabilitation" only scenario

State	Values and (in)equality	Description
1	Salmon population low, habitat quality low, rehabilitation funds are available, mortality high, habitat rehabilitation active	Habitat rehabilitation acts to reduce mortality and increase habitat quality
2	Habitat quality improving and population numbers is increasing due to reduced mortality and improved habitat.	Exact consequences depend on the life stage/habitat being targeted by the rehabilitation measures
3	Population numbers are higher but now limited by factors other than the habitat quality or life stage mortality that was addressed with rehabilitation.	Population numbers are now higher and as a consequence the numbers of fish caught by anglers and the number of anglers has increased - this results in a higher value of the fishery

5.6 Description of model fragments

The model requires a number of model fragments that describe both the static nature of the system and the processes involved. It is anticipated that a number of the mortality processes will use similar model fragments but with different (in)equality statements, value correspondences and slightly differing entities.

5.6.1 Static model fragments

A) Life stage static fragments

Each life stage (egg, juvenile, smolt and returning adult) will be represented by a static fragment that represents that each life stage has abundance and a mortality rate.

- *Condition*
  - if there is a salmon population

- *Consequence*
  - then there is life stage "x"
  - which has quantities of "number of" and a "mortality rate"

The spawning adult life stage fragment will have a natality rate rather than a mortality rate.

B) Human static fragments

Each human entity will be represented by a static fragment that represents that each entities quantities.

B1) General population
- *Condition*
  - if there is a human population

- *Consequence*
  - then there is entity "general population"
  - which utilises the river and has quantities of "pressure on system"

B2) Environment manager

- *Condition*
  - if there is a human population

- *Consequence*
  - then there is entity “environment manager”
  - which manages/rehabilitates the river and has quantities of “rehabilitation rate” of weirs, habitats, water and stocking.

B3) Anglers

- *Condition*
  - if there is a human population and a salmon population

- *Consequence*
  - then there is entity “anglers”
  - which exploit the salmon population and has quantities of “number of anglers”, “catch rate” and “value of fishery”. There are value correspondences and proportionalities between these values.

B4) Stakeholders

- *Condition*
  - if there is a river and a human population

- *Consequence*
  - then there is entity “stakeholders”
  - which utilise the river and has the quantity of “utilisation value”.

C) River static fragments

C1) Upland river

- *Condition*
  - if there is a river

- *Consequence*
  - then there is entity “upland river” and “water”
  - which has quantities of “quality of upland habitat”, “upland water quality” and “water quantity”.

C2) Lowland river

- *Condition*
  - if there is a river

- *Consequence*
  - then there is entity “lowland river” and “water”
  - which has quantities of “connectivity” and “lowland water quality”.

C3) WFD status

- *Condition*
  - if there is a river

- *Consequence*
  - Then it has quantity “WFD status”.

D) Weir static fragment

C1) Weir

- *Condition*
  - if there is a river and it has a weir

- *Consequence*
  - then there are quantities “passability of weirs” and “connectivity of river”
  - there are positive proportionalities and correspondences between these quantities.

5.6.2 Agent model fragments

WFD agent fragments that state that if there are humans then the WFD is in place and that there are different consequences if it is active or inactive. The Agent fragment can also become active if the WFD status is declining or at moderate or below. This can be seen as the equivalent of triggering the programme of measures in the WFD.

5.6.3 Process model fragments

The key processes that need to be represented are life cycle transitions, rehabilitation/degradation activities and angling.

A) Life cycle transition fragments

Each life cycle transition will have its own basic model fragment describing the relationships between numbers of each life stage and mortality and maturation/survival. These reuse the static model fragments for each stage.

A1) Natality

- *Condition*
    - if there is a salmon population and the number of spawning adults is >zero
- *Consequence*
    - then there are entities “eggs” and there is a quantity “natality rate” which is “plus”
    - there is positive influence **I+** from “natality rate” to number of eggs and a negative influence **I-** to the number of spawning adults (reflecting post spawning mortality).
    - There are correspondences between these “number of” quantities that set limit for the number of eggs a certain number of adults could produce.

A2) Survival egg to juvenile

- *Condition*
    - if there is a salmon population and the number of eggs is >zero
- *Consequence*
    - then there are entities “eggs” and “juveniles” there is a quantity “survival rate” which is “plus” and a quantity “mortality rate eggs”
    - there is positive influence **I+** from “survival rate” to number of juveniles and a negative influence **I-** to the number of eggs.
    - Then “mortality rate eggs” has value correspondences with number of juveniles to limit how many juveniles come from any number of eggs.
    - There are correspondences between these “number of” quantities that set limit for the number of juveniles a certain number of eggs could produce.

A3) Survival juvenile to smolts

- *Condition*
    - if there is a salmon population and the number of juveniles is >zero
- *Consequence*
    - then there are entities “juveniles” and “smolts” there is a quantity “survival rate” which is “plus” and a quantity “mortality rate juveniles”
    - there is positive influence **I+** from “survival rate” to number of smolts and a negative influence **I-** to the number of juveniles.
    - Then “mortality rate juveniles” has value correspondences with number of smolts to limit how many smolts come from any number of juveniles.
    - There are correspondences between these “number of” quantities that set limit for the number of smolts a certain number of juveniles could produce.

A4) Survival smolts to returning adults

- *Condition*
    - if there is a salmon population and the number of smolts is >zero

- *Consequence*
    - then there are entities “smolts” and “returning adults” there is a quantity “survival rate” which is “plus” and a quantity “mortality rate smolts”
    - there is positive influence I+ from “survival rate” to number of returning adults and a negative influence I- to the number of smolts.
    - Then “mortality rate smolts” has value correspondences with number of returning adults to limit how many adults come from any number of smolts.
    - There are correspondences between these “number of” quantities that set limit for the number of adults a certain number of smolts could produce.

A5) Survival returning adults to spawning adults

- *Condition*
    - if there is a salmon population and the number of returning adults is >zero

- *Consequence*
    - then there are entities “returning” and “spawning” adults and there is a quantity “survival rate” which is “plus” and a quantity “mortality rate returning adults”
    - there is positive influence I+ from “survival rate” to number of spawning adults and a negative influence I- to the number of returning adults.
    - Then “mortality rate returning adults” has value correspondences with number of returning adults to limit how many spawning adults result from any number of returning adults.
    - There are correspondences between these “number of” quantities that set limit for the number of spawning adults that results from a certain number of returning adults.

B) Mortality relationship fragments

This set of fragments will be required to model the relationship between the “habitat”, “water” and other river quantities and the mortality rates at each stage. These relationships will be formed from P proportionalities and value correspondences.

B1) Egg mortality is influenced by spawning habitat quality and upland water quality

- *Condition*
    - if there is a river and a salmon population

- *Consequence*
    - then there are quantities “upland river habitat quality”, “water quality” and “mortality rate eggs”.
    - There is a table of allowable values which relates the water and habitat quality to the mortality rate of eggs. In general there is a P- relationship from these “qualities” to the mortality rate. Value correspondences are used to make the calculation of the resultant mortality rate.

B2) Juvenile mortality is influenced by juvenile habitat quality and upland water quality

- *Condition*
    - if there is a river and a salmon population

- *Consequence*
    - then there are quantities “upland river habitat quality”, “water quality” and “mortality rate juveniles”.
    - There is a table of allowable values which relates the water and habitat quality to the mortality rate of juveniles. In general there is a P- relationship from these “qualities” to the mortality rate. Value correspondences are used to make the calculation of the resultant mortality rate.

B3) Smolt mortality is influenced by lowland water quality

- *Condition*
  - if there is a river and a salmon population

- *Consequence*
  - then there are quantities “lowland river water quality” and “mortality rate smolts”.
  - There is a P- relationship from water quality to the mortality rate. Value correspondences are used to fix allowable values.

B4) Returning adult mortality is influenced by river connectivity and lowland water quality

- *Condition*
  - if there is a river and a salmon population

- *Consequence*
  - then there are quantities “river connectivity”, “lowland water quality” and “mortality rate returning adults”.
  - There is a table of allowable values which relates the water quality and connectivity value to the mortality rate of returning adults. In general there is a P- relationship from these “qualities” to the mortality rate. Value correspondences are used to make the calculation of the resultant mortality rate.

C) Human process fragments

C1) Stocking process fragment

- *Condition*
  - if there is a river and a human population and anglers are dissatisfied

- *Consequence*
  - Then there are the entities “environment manager”, “juvenile salmon” and “anglers” plus the quantities “stocking rate”, “number of juvenile salmon” and “rehabilitation funds available”. There is an I+ influence from stocking rate to number of juveniles and an I- influence from stocking rate to “rehabilitation funds available”. There will also be value correspondences to set how high the numbers of juveniles can become based on the amount of funds that are available.
  - Stocking will only occur when anglers are dissatisfied and there are funds available for stocking.

C2) Habitat improvement process

- *Condition*
  - if there is a river and a human population and habitat quality is declining or less than good (or WFD status is declining or less than good)

- *Consequence*
  - Then there are the entities “environment manager”, “habitat rehabilitation rate” and “upland river” plus the quantities “habitat rehabilitation rate”, “upland river habitat quality” and “rehabilitation funds available”.
  - There is an I+ influence from rehabilitation rate to habitat quality and an I- rate from rehabilitation to funds available. There are value correspondences from funds available to habitat quality to limit the effect any amount of funds available could have on habitat quality.
  - Habitat rehabilitation rate is only active if funds are available and stops if habitat quality is above good and maintained (Ø derivative).

C3) Weir rehabilitation process

- *Condition*
  - if there is a river and a human population and weirs are present and WFD river status is less than good.

- *Consequence*
  - Then there are the entities “lowland river”, “weirs” and “environment manager” and the quantities “weirs present”, “passability of weirs”, “connectivity of river”, “weir rehabilitation rate”, “WFD status” and “rehabilitation funds available”.

- There is an **I+** influence from weir rehabilitation rate to passability of weirs and an **I-** influence to rehabilitation funds available.
- There is a value correspondence from funds available to passability that limits the effects an amount of funds used for rehabilitation of weirs can have on the passability.

C4) Water quality rehabilitation process

- *Condition*
  - if there is a river and a human population and water quality is declining or less than good (or WFD status is declining or less than good)

- *Consequence*
  - Then there are the entities “environment manager”, “water” and “river” plus the quantities “water quality rehabilitation rate”, “upland river water quality”, “rehabilitation funds available” and “WFD status”.
  - There is an **I+** from rehabilitation rate to water quality and an **I-** from rehabilitation rate to funds available for rehabilitation.
  - There are value correspondences from funds available to water quality to limit the effect any amount of funds available could have on water quality.
  - Water quality rehabilitation rate is only active if funds are available and stops if water quality is above good and maintained (Ø derivative).

C5) Angling fragment

- *Condition*
  - if there is a river and a human population

- *Consequence*
  - Then there will be entities “anglers” and “returning adult salmon” and the quantities “number of anglers”, “value of fishery”, “number of returning adult salmon” and “angler satisfaction”.
  - There is a positive proportionality P+ from “number of returning adult salmon” to the “number of anglers” and from the “number of anglers” to the “value of the fishery”.
  - There are proportionalities and value correspondences from “number of anglers” and “number of returning adult salmon” to determine the value of “angler satisfaction”.

6 DETAILED SYSTEM STRUCTURE FOR THE GREAT OUSE CASE STUDY: ENTITIES, ATTRIBUTES AND CONFIGURATIONS

6.1 Structural details

The entities and entity structure represented here summarises the key concepts and their relationships presented in previous sections.

6.1.1 Entities overview

- Human
  - General Population
  - Environment manager
  - Stakeholder
  - Anglers
- River
  - Catchment
    - Agricultural land
    - Urban areas
    - Wetlands
  - River channel
    - Spawning habitats
    - Juvenile habitats
  - Riparian zone
  - Floodplain water bodies
    - Gravel Pits
  - Water
- Fish
  - Bream (*Abramis brama*)
    - Egg
    - Juvenile
    - Sub adult
    - Adult
- Flood banks

6.2 Agents

Within the Great Ouse system the European Water Framework Directive can be seen as an Agent which affects the approach to management of the river and rehabilitation activities that might occur. The WFD provides a driver for change and for sustainable river utilisation/management.

6.3 Assumptions

Within the model there needs to be a number of assumptions to reflect what is know about bream survival, recruitment and floodplain use.

- The numbers of any life stage of bream are increased by recruitment from the previous life stage ("matures into"), are limited by the actual numbers of the previous life stage and will reduce due to maturation to the next stage and mortality acting on the life stage.
- The numbers of any life stage are limited by the availability of suitable habitats (e.g. habitat quality), this represents the carrying capacity concept. For example the number of juveniles may be limited by the quality of the riparian habitats and/or floodplain habitats.
- The survival/maturation rate is a z,p rate that has an I+ influence on the following life stage and an I- influence on the preceding life stage. It is always active unless the number of the preceding life stage is zero. The I- influence on the preceding life stage reflects maturation i.e. the reduction in the numbers of life stage x as they mature into x+1. The "plus" value of all the survival/maturation rates is equal.

- The numbers at each life stage are limited by a table of allowable values (value correspondences) between mortality rates and the numbers of life stage x-1.
- Issues regarding community level biological limiters to the population are ignored within the model.
- Human pressures and/or rehabilitation activities affect the bream population by acting on the habitat (carrying capacity) and/or on directly on the mortality process between life stages.

6.4 Quantities and quantity spaces

State variables

- **Water**
  - Water quality - the quality of water in the river affects the survival of bream
  - Water quantity - water quantity reflects water flow which affects survival of bream through flushing processes
- **Bream**
  - Number of eggs
  - Number of juveniles
  - Number of sub adults
  - Number of adults
- **River**
  - River channel habitat quality
  - Riparian zone habitat quality
  - River connectivity with floodplain
  - Abundance of floodplain water bodies
  - Biodiversity value
  - WFD status
- **Human**
  - Number of anglers
  - Human pressure on system
  - Value of fishery
  - Angler satisfaction
  - River utilisation value
  - Rehabilitation funds available
- **Flood banks**
  - Extent of flood banking

Rate variables

- **Bream**
  - Mortality rate (egg to juvenile)
  - Mortality rate (juvenile to sub adult)
  - Mortality rate (sub adult to adult)
  - Natality rate (adult to eggs)
  - Maturation/survival rate (egg to juvenile)
  - Maturation/survival rate (juvenile to sub adult)
  - Maturation/survival rate (sub adult to adult)
- **Human**
  - Flood bank rehabilitation rate
  - River channel rehabilitation rate
  - Riparian zone rehabilitation rate
  - Water quality treatment rate
  - Gravel pit creation rate

Table 6.1 Quantities and quantity spaces in the Great Ouse lowland river rehabilitation QR model

Type	Quantity	Quantity space
State		
	Water quality	Bad, poor, moderate, good, high
	Water quantity	Very low, low, medium, high, natural
	Number of eggs	Zero, v low, low, med, abundant, v abundant, high
	Number of juveniles	Zero, v low, low, med, abundant, v abundant, high
	Number of sub adults	Zero, v low, low, med, abundant, v abundant, high
	Number adults	Zero, v low, low, med, abundant, v abundant, high
	River channel habitat quality	Bad, poor, moderate, good, high
	Riparian habitat quality	Bad, poor, moderate, good, high
	River connectivity with floodplain	Zero, low, restricted, unrestricted
	Abundance of flood plain water bodies	Zero, low medium, high
	Abundance of agricultural land	Zero, low medium, high
	Abundance of urban land	Zero, low medium, high
	Abundance of wetlands	Zero, low medium, high
	WFD status	Bad, Poor, Moderate, Good, High
	Number of anglers	Zero, low medium, high
	Human pressure on system	Zero, low medium, high
	Value of fishery	Zero, low, medium, high
	Angler satisfaction	Unsatisfied, satisfied
	River utilisation value	Zero, low, medium, high
	Rehabilitation funds available	Zero, low, medium, high
	Extent of flood banking	Zero, low, medium, high, max
Rate		
	Mortality rate (egg to juvenile)	Natural, low, medium, high
	Mortality rate (juvenile to sub adult)	Natural, low, medium, high
	Mortality rate (sub adult to adult)	Natural, low, medium, high
	Natality rate (spawning adult to eggs)	Zero, plus
	Maturation/survival rate (egg to juvenile)	Zero, plus
	Maturation/survival rate (juvenile to sub adult)	Zero, plus
	Maturation/survival rate (sub adult to adult)	Zero, plus
	Flood bank rehabilitation rate	Zero, plus
	River channel habitat rehabilitation rate	Zero, plus
	Riparian habitat rehabilitation rate	Zero, plus
	Water quality treatment rate	Zero, plus
	Gravel pit creation rate	Zero, plus

6.5 Scenarios and behaviours

There are a number of scenarios that could be explored with this model. However, the key scenario is the change from the current situation in the lowland areas of the Great Ouse where there is little connection between the main river channel and the available floodplain water bodies due to flood protection measures. As a consequence the fish populations in the main channel are at a lower status than they could be. In this scenario the combination of gravel pit creation and flood bank rehabilitation can be shown to improve fish stocks and increase the amount of wetland, and consequently the wider biodiversity value, will also increase.

This basic scenario can be altered to look at the effect of the level of human pressure on the system to see what the maximum out put of rehabilitation activities could be given the socio-economic limitations present.

Table 6.2 States and behaviours in a rehabilitation scenario on the Great Ouse

State	Values and (in)equality	Description
1	Number of flood plain water bodies is low, connectivity is low, bream abundance is low, gravel pit creation rate is active, extent of flood banks is high, flood bank rehabilitation rate is inactive	This is the current situation in the Great Ouse catchment - Where WFD status is less than good
2	Number of flood plain water bodies is low but increasing, connectivity is low, bream abundance is low, gravel pit creation rate is active, extent of flood banks is high, flood bank rehabilitation rate is active - WFD agent becomes active	With the WFD agent becoming active because the WFD status is less than good then the flood bank rehabilitation rate becomes active

3	Number of flood plain water bodies is increasing, connectivity is low but increasing, bream abundance is low but increasing, gravel pit creation rate is active, extent of flood banks is high but decreasing, flood bank rehabilitation rate is active - WFD agent is active	As the flood bank rehabilitation rate becomes active the extent of flood banking starts to decrease and the connectivity of the river starts to increase. As a consequence conditions start to improve for the bream population and numbers start to improve as mortality rates start to decline and natality rates increase.
4	Number of flood plain water bodies reaches the highest it can as set by human pressure and urban areas, connectivity is a high as it can be in the scenario, bream abundance is a high as it can be in the scenario, gravel pit creation rate is inactive, extent of flood banks is as low as it can be in the scenario, flood bank rehabilitation rate is inactive - WFD agent is inactive.	The scenario finishes as the WFD status either reaches good status or the scenario stops as it has gone as far as it can given the level of human pressure on the system and the amount of urban land set in the scenario.

6.6 Description of model fragments

The model requires a number of model fragments that describe both the static nature of the system and the processes involved. It is anticipated that a number of the mortality processes will use similar model fragments but with different (in)equality statements, value correspondences and slightly differing entities.

6.6.1 Static model fragments

A) Life stage static fragments

Each life stage (egg, juvenile, sub adult and adult) will be represented by a static fragment that represents that each life stage has abundance and a mortality rate.

- *Condition*
  - if there is a bream population

- *Consequence*
  - then there is life stage "x"
  - which has quantities of "number of" and a "mortality rate"

The spawning adult life stage fragment will have a natality rate rather than a mortality rate.

B) Human static fragments

Each human entity will be represented by a static fragment that represents that each entities quantities.

B1) General population
- *Condition*
  - if there is a human population

- *Consequence*
  - then there is entity "general population"
  - which utilises the river and has quantities of "pressure on system"

B2) Environment manager
- *Condition*
  - if there is a human population

- *Consequence*
  - then there is entity "environment manager"
  - which manages/rehabilitates the river and has quantities of "rehabilitation rate" of riparian habitat, channel habitat, flood banks and water.

B3) Anglers

- *Condition*
  - if there is a human population and a bream population

- *Consequence*
  - then there is entity “anglers”
  - which exploit the bream population and has quantities of “number of anglers”, “angler satisfaction” and “value of fishery”. There are value correspondences and proportionalities between these values.

B4) Stakeholders

- *Condition*
  - if there is a river and a human population

- *Consequence*
  - then there is entity “stakeholders”
  - which utilise the river and has quantity “utilisation value”.
  - In the case of the Great Ouse a stakeholder may be a Gravel extraction company which has a gravel pit creation rate.

C) River static fragments

C1) River

- *Condition*
  - if there is a river

- *Consequence*
  - then there is entity “river channel”, “riparian zone”, “water” and “floodplain”.
  - which have quantities of “quality of river habitat”, “quality of riparian habitat”, “abundance of floodplain water bodies”, “connectivity of river to floodplain”, “water quality” and “water quantity”.

C2) WFD status

- *Condition*
  - if there is a river

- *Consequence*
  - Then it has quantity “WFD status”.

C3) Biodiversity value

- *Condition*
  - if there is a river

- *Consequence*
  - Then it has quantity “Biodiversity value”.

D) Flood bank static fragment

D1) Flood banks

- *Condition*
  - if there is a river and it has flood protection banks

- *Consequence*
  - then there are quantities “extent of flood banking” and “connectivity of river”
  - there are negative proportionalities and correspondences between these quantities.

6.6.2 Agent model fragments

WFD agent fragments that state that if there are humans then the WFD is in place and that there are different consequences if it is active or inactive. The Agent fragment can also become active if the WFD status is declining or at moderate or below. This can be seen as the equivalent of triggering the programme of measures in the WFD.

6.6.3 Process model fragments

The key processes that need to be represented are life cycle transitions, rehabilitation/degradation activities and angling.

A) Life cycle transition fragments

Each life cycle transition will have its own basic model fragment describing the relationships between numbers of each life stage and mortality and maturation/survival. These reuse the static model fragments for each stage.

A1) Natality

- *Condition*
  - if there is a bream population and the number of spawning adults is >zero

- *Consequence*
  - then there are entities “eggs” and there is a quantity “natality rate” which is “plus”
  - there is positive influence **I**+ from “natality rate” to number of eggs and a negative influence **I**- to the number of adults (reflecting natural adult mortality).
  - There are correspondences between these “number of” quantities that set limit for the number of eggs a certain number of adults could produce.

A2) Survival egg to juvenile

- *Condition*
  - if there is a bream population and the number of eggs is >zero

- *Consequence*
  - then there are entities “eggs” and “juveniles” there is a quantity “survival rate” which is “plus” and a quantity “mortality rate eggs”
  - there is positive influence **I**+ from “survival rate” to number of juveniles and a negative influence **I**- to the number of eggs.
  - Then “mortality rate eggs” has value correspondences with number of juveniles to limit how many juveniles come from any number of eggs.
  - There are correspondences between these “number of” quantities that set limit for the number of juveniles a certain number of eggs could produce.

A3) Survival juvenile to sub adults

- *Condition*
  - if there is a bream population and the number of juveniles is >zero

- *Consequence*
  - then there are entities “juveniles” and “sub adults” there is a quantity “survival rate” which is “plus” and a quantity “mortality rate juveniles”
  - there is positive influence **I**+ from “survival rate” to number of sub adults and a negative influence **I**- to the number of juveniles.
  - Then “mortality rate juveniles” has value correspondences with number of sub adults to limit how many sub adults come from any number of juveniles.
  - There are correspondences between these “number of” quantities that set limit for the number of sub adults a certain number of juveniles could produce.

A4) Survival sub adults to adults

- *Condition*
  - if there is a bream population and the number of sub adults is >zero

- *Consequence*
  - then there are entities “sub adults” and “adults” there is a quantity “survival rate” which is “plus” and a quantity “mortality rate sub adults”
  - there is positive influence **I**+ from “survival rate” to number of adults and a negative influence **I**- to the number of sub adults.

  - Then "mortality rate sub adults" has value correspondences with number of adults to limit how many adults come from any number of smolts.
  - There are correspondences between these "number of" quantities that set limit for the number of adults a certain number of sub adults could produce.

B) Mortality relationship fragments

This set of fragments will be required to model the relationship between the "habitat", "water" and other river quantities and the mortality rates at each stage. These relationships will be formed from P proportionalities and value correspondences.

B1) Egg mortality is influenced by spawning habitat quality and water quality

- *Condition*
  - if there is a river and a bream population

- *Consequence*
  - then there are quantities "river habitat quality", "water quality" and "mortality rate eggs".
  - There is a table of allowable values which relates the water and habitat quality to the mortality rate of eggs. In general there is a P- relationship from these "qualities" to the mortality rate. Value correspondences are used to make the calculation of the resultant mortality rate.

B2) Juvenile mortality is influenced by juvenile habitat quality, water quality and water quantity

- *Condition*
  - if there is a river and a bream population

- *Consequence*
  - then there are quantities "river habitat quality", "water quality", "water quantity" and "mortality rate juveniles".
  - There is a table of allowable values which relates the water quality/quantity and habitat quality to the mortality rate of juveniles. In general there is a P- relationship from these "qualities" to the mortality rate. Value correspondences are used to make the calculation of the resultant mortality rate.

B3) Sub adult mortality is influenced by river channel quality and the availability of floodplain water bodies

- *Condition*
  - if there is a river and a bream population

- *Consequence*
  - then there are quantities "river habitat quality", "availability of floodplain waterbodies" and "mortality rate sub adults".
  - There is a P- relationship from habitat quality and availability of floodplain waterbodies to the mortality rate. Value correspondences are used to fix allowable values.

C) Human process fragments

C1) Flood bank rehabilitation process fragment

- *Condition*
  - if there is a river and a human population and WFD status is declining or below good

- *Consequence*
  - Then there are the entities "environment manager", "rehabilitation funds available" "extent of flood banking", "extent of urban areas", "river connectivity", "flood banking rehabilitation rate" and biodiversity value. There is an I- influence from rehabilitation rate to "extent of flood banking" (OR an I+ to river connectivity) and an I- influence from rehabilitation rate to "rehabilitation funds available". There will also be value correspondences to set how low the extent of flood banking can become based on the amount of funds that are available and also the "extent of urban land".
  - Flood bank rehabilitation is driven mainly by the WFD agent and is limited by human pressure in the system and the extent of urban land.
  - Increasing connectivity will have a positive proportionality with biodiversity value and the amount of wetland.

C2) Habitat improvement process

- *Condition*
  - if there is a river and a human population and (channel or riparian) habitat quality is declining or less than good (or WFD status is declining or less than good)

- *Consequence*
  - Then there are the entities “environment manager”, “habitat rehabilitation rate” and “river” plus the quantities “habitat rehabilitation rate”, “habitat quality”, WFD status and “rehabilitation funds available”.
  - There is an I+ influence from rehabilitation rate to habitat quality and an I- rate from rehabilitation to funds available. There are value correspondences from funds available to habitat quality to limit the effect any amount of funds available could have on habitat quality.
  - Habitat rehabilitation rate is only active if funds are available and stops if habitat quality is above good and maintained (Ø derivative).

C3) Water quality rehabilitation process

- *Condition*
  - if there is a river and a human population and water quality is declining or less than good (or WFD status is declining or less than good)

- *Consequence*
  - Then there are the entities “environment manager”, “water” and “river” plus the quantities “water quality rehabilitation rate”, “water quality”, “rehabilitation funds available” and “WFD status”.
  - There is an I+ from rehabilitation rate to water quality and an I- from rehabilitation rate to funds available for rehabilitation.
  - There are value correspondences from funds available to water quality to limit the effect any amount of funds available could have on water quality.
  - Water quality rehabilitation rate is only active if funds are available and stops if water quality is above good and maintained (Ø derivative).

C4) Angling fragment

- *Condition*
  - if there is a river and a human population

- *Consequence*
  - Then there will be entities “anglers” and “adult bream” and the quantities “number of anglers”, “value of fishery”, “number of adult bream” and “angler satisfaction”.
  - There is a positive proportionality P+ from “number of adult bream” to the “number of anglers” and from the “number of anglers” to the “value of the fishery”.
  - There are proportionalities and value correspondences from “number of anglers” and “number of returning adult salmon” to determine the value of “angler satisfaction”.

C5) Gravel pit creation fragment

- *Condition*
  - if there is a river and a human population

- *Consequence*
  - Then there will be the entities “floodplain water bodies” and “Stakeholders”.
  - There will be the quantities “gravel pit creation rate”, “abundance of flood plain water bodies” and “utilisation value”.
  - Gravel pit creation rate will have an I+ influence on the “abundance of floodplain water bodies” and will also have an I+ influence on the “utilisation value”.

7 CONCLUSIONS

These two case studies look at two different problems of fish population and river rehabilitation. However, both problems are generally addressed using similar ideas and approaches. The common theme is that rehabilitation attempts to address the factors/processes that are limiting the recruitment and survival of the fish population and/or community. In both cases the major issues are habitat quality and the connectivity between the available habitats. In the case of salmon in the Trent it is the longitudinal connectivity between the smolt/adult feeding habitats in the sea and the spawning habitats in the upland river tributaries. In the Great Ouse catchment it is the connectivity between the main river channel and floodplain water bodies that can be important spawning and juvenile habitats as well as habitats for adult life stages. In addition the connected flood plain water bodies can act as important refuges from high flow events which could have impact on the mortality rates of juveniles.

Given these similarities both situation can be addressed using a common structure of a fish population life cycle - looking at the influence of rehabilitation and environmental conditions on the mortality/survival between each life stage. The challenge for modelling will be calculating the value correspondences and the tables of allowable values in given situations.

In addition to the biological processes both model build in elements of socio-economic factors that set the scene and/or benefit from rehabilitation activities. In both cases angling is considered and also the WFD is considered as an agent that drives rehabilitation. Additionally both models consider the effect of human population and stake holder pressure on what is actually possible with rehabilitation measures. Again, the challenge for this aspect of the modelling will be modelling the value correspondences and the tables of allowable values to limit the effects of rehabilitation in each scenario. It is probable that the structure of these tables of allowable values and value correspondences will change and be modified during the modelling process as problems, unexpected behaviours and ambiguities are discovered.

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