Integrative qualitative modelling of ecological and socio-economic aspects of river-rehabilitation in England

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Abstract

This poster present the planning phase of a QR model following the structured modelling approached described by Bredeweg *et al.* (2007). The model is aimed at exploring issues and outcomes for rehabilitation of Atlantic salmon stocks in the River Trent. These stocks have been lost due to impacts from the industrial revolution. Rehabilitation programmes within the context of the European Union's legislation for sustainable water management require that ecological status be balanced alongside socio-economic needs of society. This model uses the ecological processes of the salmon life cycle as a focus around which socio-economic factors of rehabilitation are also modelled. The completed model could be applied as a tool for environmental managers, scientific researchers and stakeholders to learn about rehabilitation programs and their potential outcomes.

Introduction

This paper describes development of a Qualitative Reasoning (QR) modelling case study which was developed as part of the EU funded NaturNet-Redime (NNR) project (Sixth Framework Program, Project no. 004074 http://www.naturnet.org). This project contributes to the European Union's Strategy for Sustainable Development (European Commission 2001) in the context that the NNR project revolves around developing new technologies (of which QR is one example) for use within a general educational setting, for exploration of sustainable development issues. One of the goals of the NNR project was to improve the Garp3 QR software tool and to construct guidelines for a standardised approach to QR modelling (Bredeweg *et al*. 2007). Within the QR component of the NNR project five case studies were developed, which contribute to creating programmes for education about sustainability (see Salles *et al.*, Cioaca *et al.*, Nakova *et al*., and Zitek *et al*. also submitted to this QR workshop). All these case studies focus on issues pertaining to aquatic ecology and sustainable management of freshwater ecosystems. The case study presented here focuses on the modelling of species life cycles within the context of river rehabilitation programmes. As such the case study addresses the issues of sustainability of aquatic resource management, an issue that is currently of great concern in the European Union. The European Water Framework Directive (WFD) (EU 2000) provides legislation for a standardised approach to the sustainable management of water resources in the European Union. As such management and rehabilitation of rivers under the WFD represents an example of sustainable development.

River rehabilitation projects in the UK are often targeted to economically valuable fish species (e.g. Atlantic salmon, *Salmo salar* L.). Conservation and management of these species is often based around quantitative life cycle models (e.g. Aprahamian, Wyatt & Shields, 2006) which examine the recruitment of individuals to each consecutive life stage to identify the factors that are impinging on, or limiting the size of, the population. Hence, planning of rehabilitation activities focuses on the key human activities that impact on the life cycle of the fish populations/community being managed. In this context, QR modelling of rehabilitation issues based around a species life-cycle model has the potential to provide a basis for environmental managers, researchers, stakeholders and students to investigate the potential outcomes and conflicts within a given rehabilitation programme. Indeed, QR modelling has been previously used to examine the functioning of Atlantic salmon redds (spawning areas) (Guerrin & Dumas 2001a,b). However, this model focused only on one phase during the life cycle. A QR model which encompasses a full life cycle, together with the socio-economic factors of sustainable management, may be an extremely valuable tool.

The goal of this paper is to describe the formulation of the case study following the "structured approach to qualitative modelling" as described by Bredeweg *et al.* (2007). The standard approach describes four main steps to be undertaken during the formulation and planning of a

QR model. These steps are designed to focus the modeller on: 1) describing the general *model system* and *model goals* within the context of the domain specific concepts of the case study (including concept maps using domain specific terminology); 2) identification and specification of the key components of the model system; 3) description of potential scenarios and general *global behaviours* expected, and 4) *detailed specification of model system structure* using Garp3 terminology. All these elements contribute to a detailed model plan prior to implementation in the Garp3 QR software. This paper presents the outputs from these fours steps; the model itself is currently being implemented in Garp3 and will be forthcoming.

Model System

Prior to the industrial revolution, the River Trent had diverse and prolific fish stocks, and supported good fisheries. However, with the expansion of industry, the fishery began to decline, and water quality reached its lowest level in the 1950s. 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. The decline in catches from the 1880s onwards was almost certainly because of pollution and obstructions to the passage of migrating adult salmon (e.g., weirs used for water regulation; Cowx, 1986; Cowx & O'Grady, 1995a, b; Sykes, 2004). 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).

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 (i.e., weirs) on the Trent may detrimentally affect other user groups and impede continued development of other resources in the Trent catchment. If salmon are re-introduced, these conflicts between users will have to be resolved through negotiation with the various user groups. 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.

Main Model Goals

A QR model for this case study could provide a tool that:

1. enables stakeholders, environmental managers, researchers and students to investigate factors limiting salmon stocks in the River Trent, to learn what activities are required to re-establish a salmon fishery in the River

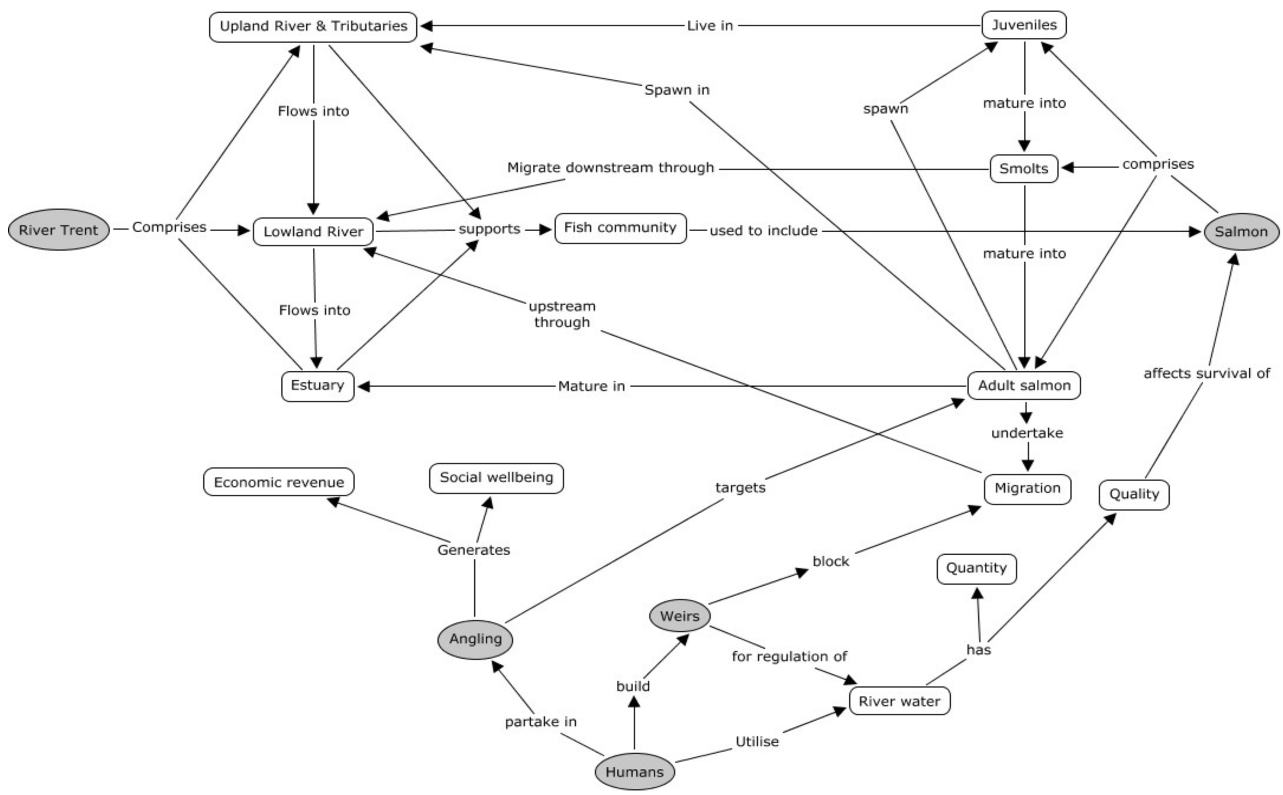

Figure 1. Concept map for salmon rehabilitation in the River Trent.

Trent, to describe the potential outcomes of rehabilitation activities and to identify potential stakeholder conflicts;

2. shows potential socio-economic benefits of re-establishing a salmon fishery, together with the socio-economic costs of rehabilitation both to the fishery and other river users.

Concept Map

The first stage in the structured modelling approach was to construct a concept map that helps identify, clarify, and focus knowledge about the system of interest (Figure 1). This concept map captures the domain knowledge that Atlantic salmon is a migratory species that reproduces in the upper reaches of rivers, but grows to maturity in the North Atlantic Ocean. Adult salmon spawn (lay eggs) into redds (nests), which the adult salmon dig in suitable gravel substrates of the river bed. Juvenile salmon remain resident in fresh water until they attain a size at which, as "smolts", they can migrate down river to the estuary and open ocean. The concept map indicates the key life stages in a salmon population, the different habitats they utilize, the way humans directly exploit salmon and how human activities can damage the salmon population. This concept map also helps define the *entities* in the model system (physical objects or abstract concepts that play a role within the system) and the contextual relations between them (termed *configurations* in Garp3).

System structure

The entity hierarchy and system structure (the way entities in the model relate to each other, and the configurations between them) for the model are designed to account for the different life stages of a salmon population, the different habitats in a river and the different sections of human society that may influence, or be influenced by, rehabilitation projects. Essentially, the model has four entities: human, salmon, river and weirs. These are divided into a number of sub-entities as follows:

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

Global Behaviour

Main Processes

The model for the rehabilitation of the Atlantic salmon populations of the River Trent is designed to capture life cycle processes that are integral in sustaining a viable salmon population. The life cycle processes that are generally considered within rehabilitation programmes are mortality/survival, natality, migration, individual growth/maturation, and immigration (from neighbouring populations). This 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.

Given that the case study objectives are for the socio-economic aspects of river rehabilitation to be captured in a QR model, there are a number of human activities that can be seen as integral processes. According to expert reviews of the Trent (Cowx, 1986; Cowx & O'Grady, 1995a, b; Sykes, 2004) the key human activities that affect the system and should be included are pollution, habitat degradation, river regulation (for a variety of purposes e.g. abstraction, hydropower generation etc.) and salmon angling (exploitation of returning adult salmon).

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 should be considered are mitigation or removal of barriers (weirs and fish passes), stocking of juvenile salmon, waste water treatment, appropriate management of abstraction and rehabilitation of habitat.

Causal Model

In the salmon life cycle model (Figure 2) which forms the focus of the River Trent case study, the numbers of each life stage are regulated by the natality rate, recruitment rates and mortality rates between each life stage. Each recruitment rate acts to increase (through positive directed influences, I+ in Garp3) the numbers of the next life stage whilst also reducing the numbers of the previous life stage (through negative directed influences, I- in Garp3). This reflects the maturation process. The activity of the recruitment rate is controlled by a table of allowable values between the numbers of the previous life stage and the

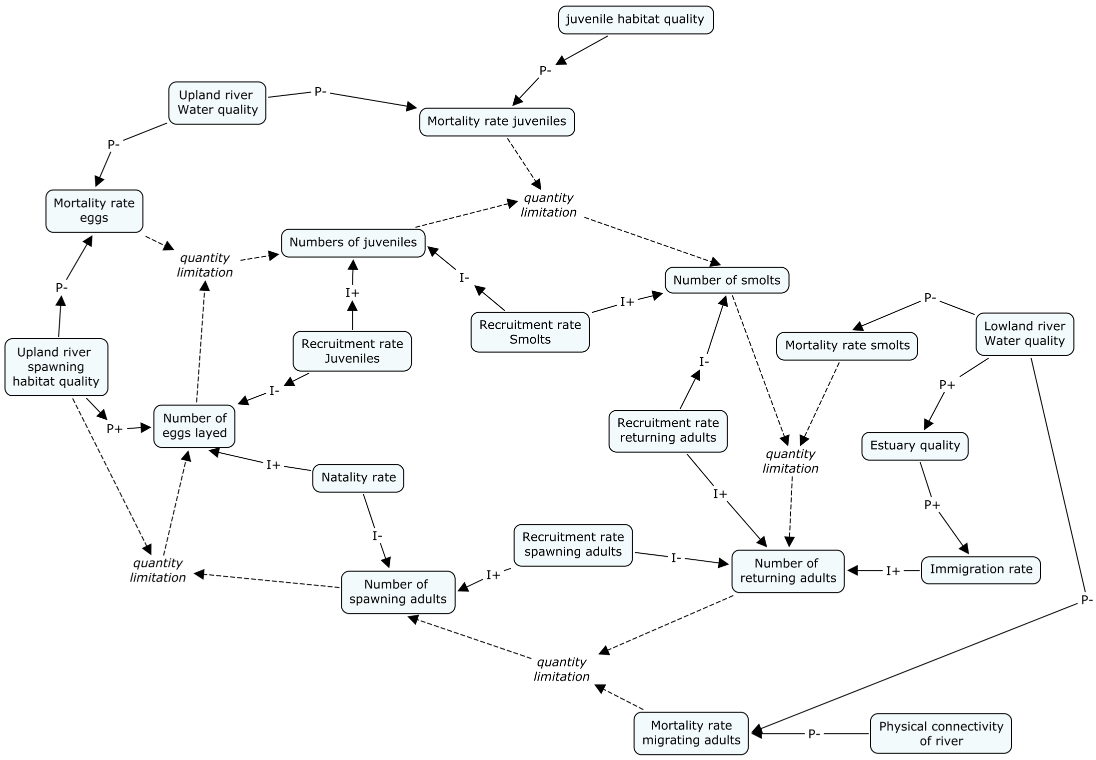

Figure 2. Causal model for the salmon life cycle which forms a focus for the overall QR model. "I" indicates a directed influence and "P" indicates a proportionality within the Garp3 software.

mortality rate of the previous life stage (e.g. Table 1). In this situation the magnitudes of each recruitment 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 controls how many of the previous life stage survive to recruit to the subsequent life stage. For each of the human activities, the intensity of the activity acts to alter the mortality rates between specific life stages. These human activities affect the mortality rates through positive (P+) and negative (P-) proportionalities in the Garp3 software.

Table 1 Matrix of allowable values for the number of life stage x+1 based on the combined values of number of life stage x and the mortality that is applied.

N life stage x+1 Matrix		Level of mortality / increase in mortality			
		Natural	Low	Medium	High
N life stage x	High	*High*	*High*	*Medium*	*Low*
	Medium	*Medium*	*Medium*	*Low*	*Very low*
	Low	*Low*	*Low*	*Very low*	*Very low*
	Very low	*Very low*	*Very low*	*Very low*	*Zero*
	Zero	*Zero*	*Zero*	*Zero*	*Zero*

Scenarios

There are two main scenarios and behaviours that can be explored with this model. Within these two main scenarios a whole suite of specific scenarios could be developed depending on the type of end-user and their existing knowledge. These scenarios are envisioned to be used by environmental managers to demonstrate to stakeholders or students the variety of critical bottlenecks to establishment of salmon populations and the likely outcomes of proposed rehabilitation measures.

1) Salmon population exists.
This type of scenario can be used to explore the effects of human activities in a system where a salmon population is present and is under threat from human pressures.
2) Salmon population absent due to physical barriers to migration (actual situation).
This scenario could have many variations depending upon how much rehabilitation was feasible based on socio-economic conditions and other external factors. Within this group of scenarios two particular scenarios/behaviours can be explored:

A. "Stocking only scenario" - In this scenario salmon are absent from the Trent but the environmental 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.

B. "Stocking plus rehabilitation of weirs" - This scenario is similar to A except that at the same time environmental 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.

Detailed System Structure and Behaviour

The case study described above is being developed in the Garp3 collaborative QR modelling workbench. The software provides a structured approach to organizing causal dependencies into a series of model fragments (partial models which are composed of multiple ingredients capturing one concept about the model system). Within the structured approach to modelling the model planning phase includes definition of a detailed system structure and behaviour. One key element of this section is the textual description of model fragments in terms of the conditions for them to be active, the consequences of their activity, including dependencies and assignments of qualitative values (via correspondences, calculations, or inequalities). Textual descriptions of model fragments serve to guide implementation within the Garp3 workbench. For the purposes of this paper, only a few model fragments are described as examples.

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/recruitment. For example:

Recruitment egg to juvenile

- *Condition*
  - if there is a salmon population and number of eggs > zero
- *Consequence*
  - then there are entities "eggs" and "juveniles" and there is a quantity "recruitment rate" which is "plus" and a quantity "mortality rate eggs"
  - there is positive influence I+ from "recruitment 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 limits for the number of juveniles a certain number of eggs could produce.

These recruitment fragments are required so that conceptually there is a process which increases the numbers of life stage x+1 whilst at the same time reducing numbers at life stage x. This is equivalent to maturation from x to x+1. As all these rates are equal, the numbers of each life stage will not change unless altered by changes in mortality rates which limit how many of life stage x+1 can survive from a number of life stage x under a certain mortality rate.

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 are effectively proportionalities and value correspondences. For example:

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.

These model fragments determine how many individuals of life stage x+1 can be produced from a number of individuals in life stage x, based on the mortality rate. In this context, mortality rate is linked to the quality and quantity of habitats available for each life stage and as such reflects the ecological concept of carrying capacity of the ecosystem.

Conclusions

This case study represents a challenging field of ecological modelling where both ecological processes and socio-economic factors are modelled in a single integrative model. One of the biggest challenges in terms of modelling the ecology is to model the recruitment and mortality processes in a way that gives the required population behaviours. One of the challenges here is to capture the true nature of transitions from one stage to another in qualitative terms through the use of informative quantity spaces and value correspondences. Only once these can be modelled properly can the socio-economic factors be assessed, and the effects of rehabilitation activities be properly judged. If these can all be built into a single integrative model then it could prove to be an extremely useful and flexible tool for education, research and project planning, including identification of potential conflicts.

As the model is being built around some general ecological principles, it could be adapted for other rehabilitation situations and species. For example this model is also being developed for use in a case study of lowland floodplain river rehabilitation using common bream as an indicator species. Transferability of a standard model between systems may provide scope for common assessment of sustainable rehabilitation activities and comparisons between systems and different rehabilitation activities.

One of the issues of using qualitative reasoning modelling for investigations which involve a range of end-users is that to understand the outputs the user needs to understand both the domain expertise and the terminology and concepts within QRM. One of the key benefits of the standardised approach to modelling proposed by Bredeweg *et al.* (2007) is that the structured textual descriptions give the modeller a framework to use to translate domain knowledge into QR vocabulary and settings. The transition of domain concepts into a Garp3 model is not always an easy process and the construction of a causal model using QR terminology gives a useful framework to build on when the model is implemented. However, the main difficulty in developing a causal model prior to implementation is that it is not always clear whether relationships should be qualitative proportionalities (P+/P-) or direct influences (I+/I-) or indeed some form of correspondence. In such a situation it would be useful to initially develop a causal model where the relationships are described only as positive, negative and/or some form of value limitation. Once this "domain" causal model was described fully the process of developing it into a full QR causal model could be undertaken. The transition from domain causal model to QR causal model would also act as a modelling phase that identified where one quantity was acted on by more than one other quantity. This process would facilitate the determination of the most appropriate choice of I's and P's and how to combine the influences of a number of quantities.

The documentation then also allows end users to understand both the domain knowledge and how it has been represented into a QR model. Such a structured approach is also imperative for the evaluation of models from the point of view of both domain experts and other QR modellers. Within the NatureNet-Redime project a range of end-users (students, researchers etc.) will use both the textual description of the model and the final model (once fully implemented in Garp3) itself to evaluate the models domain content, QR interpretation and potential application.

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References

Aprahamian M.W., Wyatt R.J. & Shields B.A. (2006) Use of biological reference points for the conservation of Atlantic salmon, *Salmo salar*, in the River Lune, North West England. *Fisheries Management and Ecology* **13**, 21-30.

Bredeweg B., Salles P., Bouwer A., Liem J., Nuttle T., Cioaca E., Nakova E., Noble R., Rios Caldas A.L., Uzanov Y., Varadinova E. & Zitek A. (2007, in press) Towards a Structured Approach to Building Qualitative Reasoning Models and Simulations. *Ecological Informatics*.

Cowx I.G. (1986). *The case for the re-introduction of salmon into the River Derwent*. Derbyshire County Angling Club Report 54 pp.

Cowx I.G. & O'Grady K.T. (1995a) *The reintroduction of salmon in the River Dove via the River Trent*. Report to the National River Authority Severn Trent Region Nottingham 98 pp.

Cowx I.G. & O'Grady K.T. (1995b) *Feasibility of upstream movement of salmon at Holme sluices on the River Trent at Nottingham*, Report to the National River Authority Severn Trent Region Nottingham 12 pp.

European Commission. 2001. Communication from the European Commission: a Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development. Brussels, Belgium.

EU (2000) *Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000 establishing a framework for community action in the field of water policy*. The European Parliament and the Council of the European Union, 72 pp.

Guerrin F. & Dumas J. (2001a) Knowledge representation and qualitative simulation of salmon redd functioning. Part I: qualitative modelling and simulation. *Biosystems* **59**, 75-84.

Guerrin F. & Dumas J. (2001b) Knowledge representation and qualitative simulation of salmon redd functioning. Part II: qualitative model of redds. *Biosystems* **59**, 85-108.

Sykes A.J.A (2004) Feasibility study for the revival of migratory salmonid stocks within the rivers of the Humber catchment. MSc Thesis, University of Hull, 141pp.