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Qualitative modelling of limiting factors for a salmon life cycle in the context of sustainable river rehabilitation

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1. MODEL BACKGROUND

This paper describes aspects of a Qualitative Reasoning (QR) model 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 contributed to the European Union's Strategy for Sustainable Development [European Commission 2001] in the context that the NNR project revolved 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]. The model presented here was developed following this standardised modelling approach and focused on the representation of a species life cycle 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.

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. 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. In this context, such a QR model could be used to provide a basis for environmental managers, researchers, stakeholders and students to investigate the potential outcomes and conflicts within a given rehabilitation programme.

2. MODEL STRUCTURE, ISSUES AND SOLUTIONS

The model was developed in the Garp 3 QR modelling environment which allows knowledge about concepts, properties and processes to be integrated in the form of model fragments (a sub-unit of a model describing a particular aspect of the system) and scenarios which integrate the knowledge from many model fragments in the form of scenarios, simulations and behaviours. The whole scenario of this model follows the concept of the life cycle and the influence human activities have on habitat quality and consequently on the survival of individuals at each life stage (each life stage is considered to be an individual population). In the model each life stage recruits into the next life stage from adult to egg to juvenile to smolt back to adult. Each life stage inhabits a particular river type (eggs and juveniles in upland river; adults migrating through a lowland river) and particular habitat type (eggs in spawning habitat; juveniles in juvenile habitat). The river types flow through catchments (upland and lowland) in which human activity occurs in the form of degradation agents which affect the habitat and river quality for a specific life stage.

The key concepts within the life cycle are the different life stages and the survival of an individual from one life stage to the next is the fundamental process which needs to be represented by the system. In this context each life stage is considered to be an independent population within the model. The basic concepts for a population are described by a number of model fragments which describe the quantities "*Number recruited*" and "*Number surviving*" for a life stage. Within the model the concepts of mortality, survival and the *Numbers surviving* within each life stage, and the factors controlling it, were implemented using the following concepts:

1) The *Numbers surviving* a particular life stage are limited by either or both of the *Numbers recruited* to the life stage and the *Habitat quality* (whichever is lesser) – the maximum size limit of the *Numbers surviving* in any situation can be considered as a quantity, the *Population potential*.
2) The *Numbers surviving* is limited by the *Population potential* and changes in response to being >, < or = to the potential.
3) The changes in the *Numbers surviving* (due to an imbalance with *Population potential*) result from changes in the balance of the level of recruitment and the mortality/survival rates – the net effect of these two rates can be modelled as a single quantity, the *Net survival dynamic*.

Following this *Population potential* is a conceptual quantity that is a combination of the *Number recruited* and the *Habitat quality* which was implemented using complex value correspondences between the controlling variable and the *Population potential* (where the controlling quantity was the quantity with the lesser magnitude). The *Numbers surviving* is then controlled by a directed influence from the *Net survival dynamic* which itself is derived as a calculus *Population potential* minus *Numbers surviving*.

Interrogation of the behaviour paths and dependency diagrams during the model development indicated inconsistent behaviour relating to the derivative behaviour of *Net survival dynamic* when both *Numbers recruited* and *Habitat quality* resulted in a dynamic behaviour of *Population potential*. In particular the inconsistent behaviours were caused in situations when either:

1) *Population potential* > *Numbers surviving* (i.e. *Net survival dynamic* is plus), δ *Population potential* is plus and is bigger than δ *Numbers surviving* which is also plus (due to I+ from *Net survival dynamic*) OR
2) *Population potential* < *Numbers surviving* (i.e. *Net survival dynamic* is minus), δ *Population potential* is minus and is less than δ *Numbers surviving* which is also minus (due to I+ from *Net survival dynamic*).

In these situations the resultant is that *Net survival dynamic* is either 1) plus and increasing or 2) minus and decreasing. The behaviour paths in this situation become inconsistent in a situation where the derivative of *Population potential* becomes steady. At this point the configurations of model fragments indicate that in:

Situation (1) *Net survival dynamic* should be plus and decreasing (as the difference between *Population potential* and *Number surviving* is now getting smaller because the value of *Population potential* is steady and the value of *Number surviving* is increasing due to the I+ from *Net Survival dynamic*), and in;

Situation (2) *Net survival dynamic* should be minus and increasing. In both cases this is an inconsistent behaviour as logically the derivative of *Net survival dynamic* must pass through "steady" to move from increase to decrease of vice versa.

The easiest solution to remove this inconsistent behaviour within the current configuration of model fragments was to eliminate them as possible behaviours in each situation (*Habitat quality > Number recruited*; *Habitat quality < Number recruited*; *Habitat quality = Number recruited*). This was done by constraining the possible derivative values of *Net survival dynamic* in situations for each of its magnitudes (minus, zero, plus) using a complex suite of model fragments.

4. CONCLUSIONS

Whilst the model implemented in GARP 3 to explore the salmon life cycle was able to explore scenarios related to single or pairs of life stages, it is currently unable to explore scenarios relating to the full life cycle. This is due to the complexity and size of simulations required to consider all life stages and their dynamics of changing recruitment and survival even if human activity (degradation and rehabilitation) is only considered for a single life stage in the life cycle. The majority of this complexity is due to the fact that the modelling approach allows some flexibility for the relative rates of changes for the *Number surviving* at each life stage, in response to the changes in the *Population potential* that is generated by the exogenous behaviours of rehabilitation activities, and their effect on habitat quality. The development of this complex model has led to research into potential developments in the Garp 3 modelling environment to aid the construction and simulation of large complicated models. In addition, the model raised fundamental issues in QR for the use of calculus of quantities with dynamic magnitudes. Ideally a general, and simpler, solution to model such a basic calculus concept is required.

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