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QR models and documentation for the implementation of 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

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Content

Executive summary

This document is the textual description of the implementation of qualitative models in the GARP 3 modelling environment of the case study on rehabilitation of the Rivers Trent and Great Ouse in the UK. The model presented here was developed using the framework to qualitative modelling described by Bredeweg *et al.* (2005, 2007). This deliverable builds upon the planning of the model described in project deliverable D6.5.1 “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” (Noble & Cowx 2006).

The final model presented in this deliverable integrated modelling concept that relate to the species life cycles of common bream and Atlantic salmon, two species that can be considered as indicator species for lowland floodplain rivers and upland rivers respectively. The final model integrates concepts relating to survival and mortality within and between (recruitment) life stages, together with the concepts relating human activities and rehabilitation activities to the quality of the river habitats used be individual life stages of each species. The model was implemented so that general concepts that applied to both species were modelled in a way that the model fragments could be applied to both aspects of the case study. In this way general concepts that applied to both systems could be explored in scenarios that were independent of the specific details that applied to each river system. This modelling approach also meant that the model fragments which relate to the general concepts may potentially be reused in other models and by other models in the future.

The modelling approach was designed around scenarios which considered the life cycle of each of the species and how human activities were related to specific habitats used by individual life stages. However, the complexity of multi-life stage models, especially when these were considered within a cyclical complex, meant that these large scenarios were too large to be simulated and explored within the GARP 3 environment. However, smaller scenarios which focussed on single or pairs of life stages were developed which allow the model user to explore the key concepts of the ecology and socio-economic factors in river rehabilitation projects.

1 INTRODUCTION

1.1 Background to UK case studies

This document contains the results and conclusions of the implementation of the UK case studies as Qualitative Reasoning models within the GARP3 modelling environment, following the modelling guidelines of Bredeweg *et al.* (2005, 2007). The document builds on the model plans developed in Deliverable 6.5.1 "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" (Noble & Cowx 2006). This section provides only a brief summary that document and the case studies and their background. The UK case study was designed to consider river rehabilitation and sustainable development issues in two contrasting river systems. Therefore, the case study considered the rehabilitation of a migratory Atlantics salmon (*Salmo salar* L.) population in the River Trent and rehabilitation of a lowland floodplain river, the Great Ouse.

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. Figures 1.1 and 1.2 provide a summary of the conceptual structure of the relationship of salmon life stages with different river habitats (Figure 1.1) and the elements of rehabilitation that need to be considered (Figure 1.2).

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. This case study used a typical lowland fish species, the common bream (*Abramis brama* L.) as a focal point for the model. Figures 1.3 and 1.4 provide a summary of the conceptual structure of the relationship of bream life stages with different river habitats (Figure 1.3), and the elements of rehabilitation that need to be considered (Figure 1.4).

As detailed in Noble & Cowx 2006 the similarities in the conceptual structure of the systems a single modelling approach could be used based around a generic scenario structure and generic model fragments that modelled key processes and behaviours that were common to both systems. In this way a common model could be used to explore both systems and show the similarities in the concepts of management and sustainable development that apply to all systems.

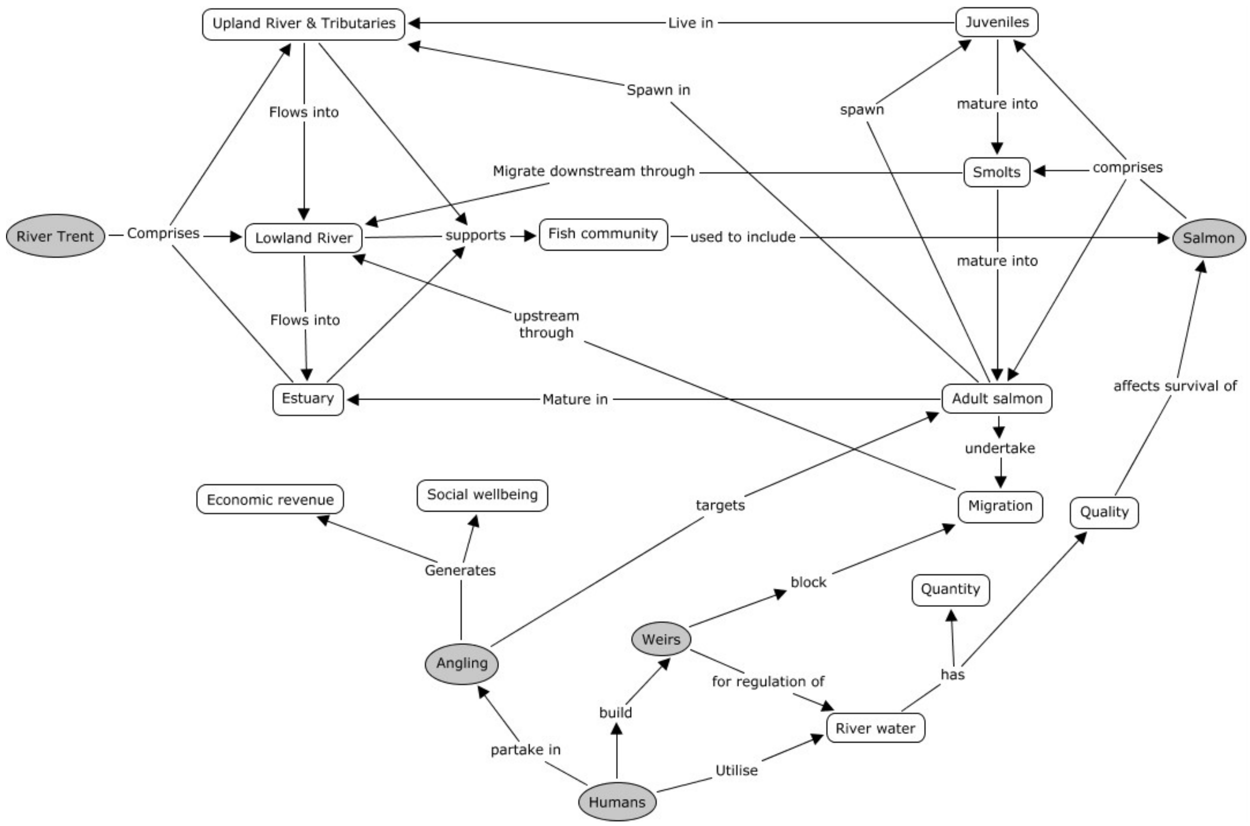


Figure 1.1 Concept map highlighting some aspects of the salmon life cycle in the context of angling and human use of the River Trent.

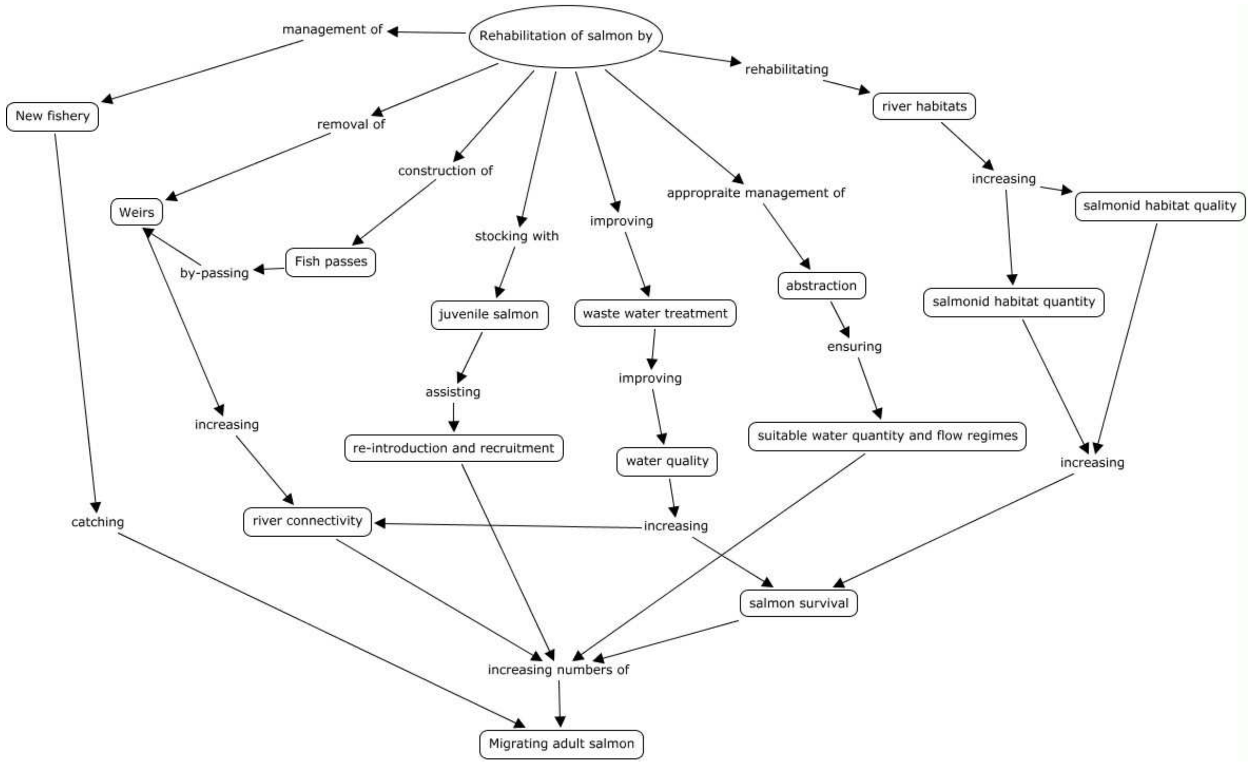


Figure 1.2 Rehabilitation activities required to re-introduce a viable salmon population and associated fishery in the River Trent.

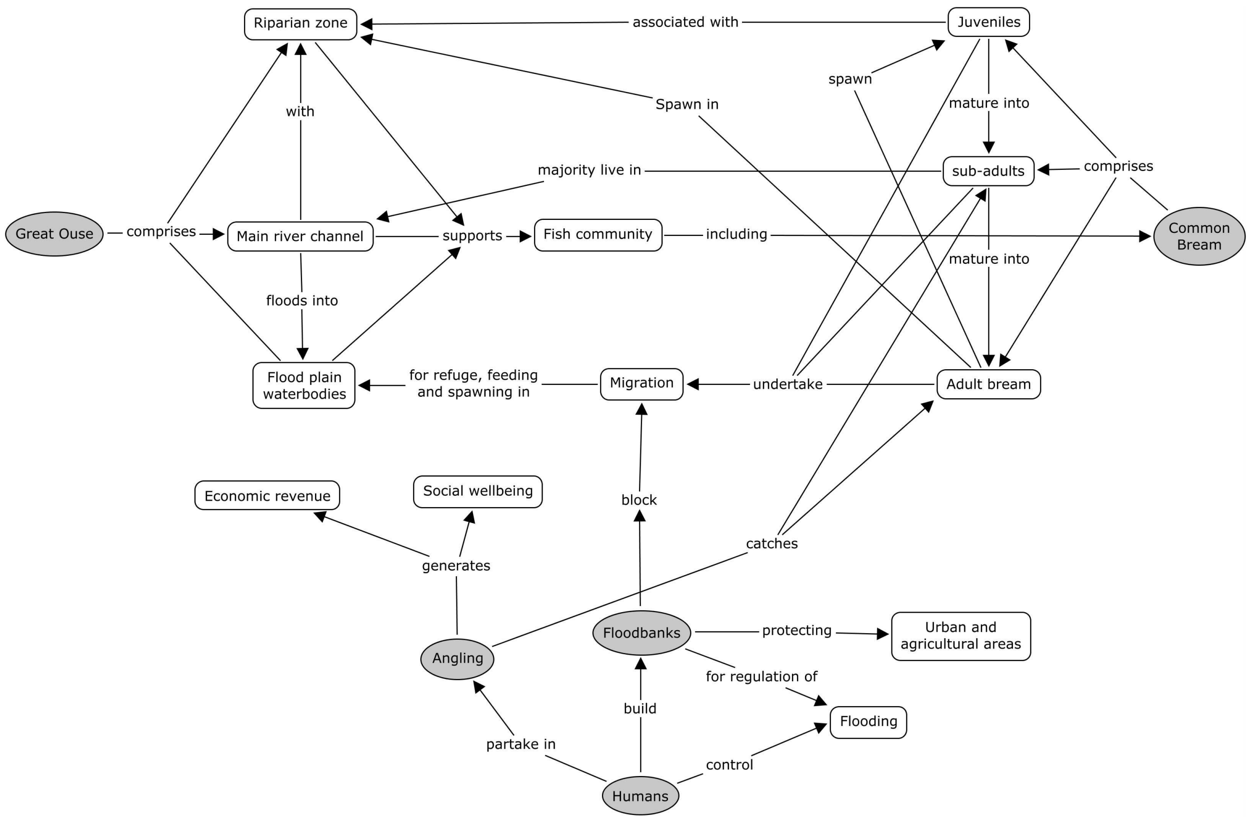


Figure 1.3 Concept map of the relationships between different life stages of a bream population and different habitats within the lowland Great Ouse.

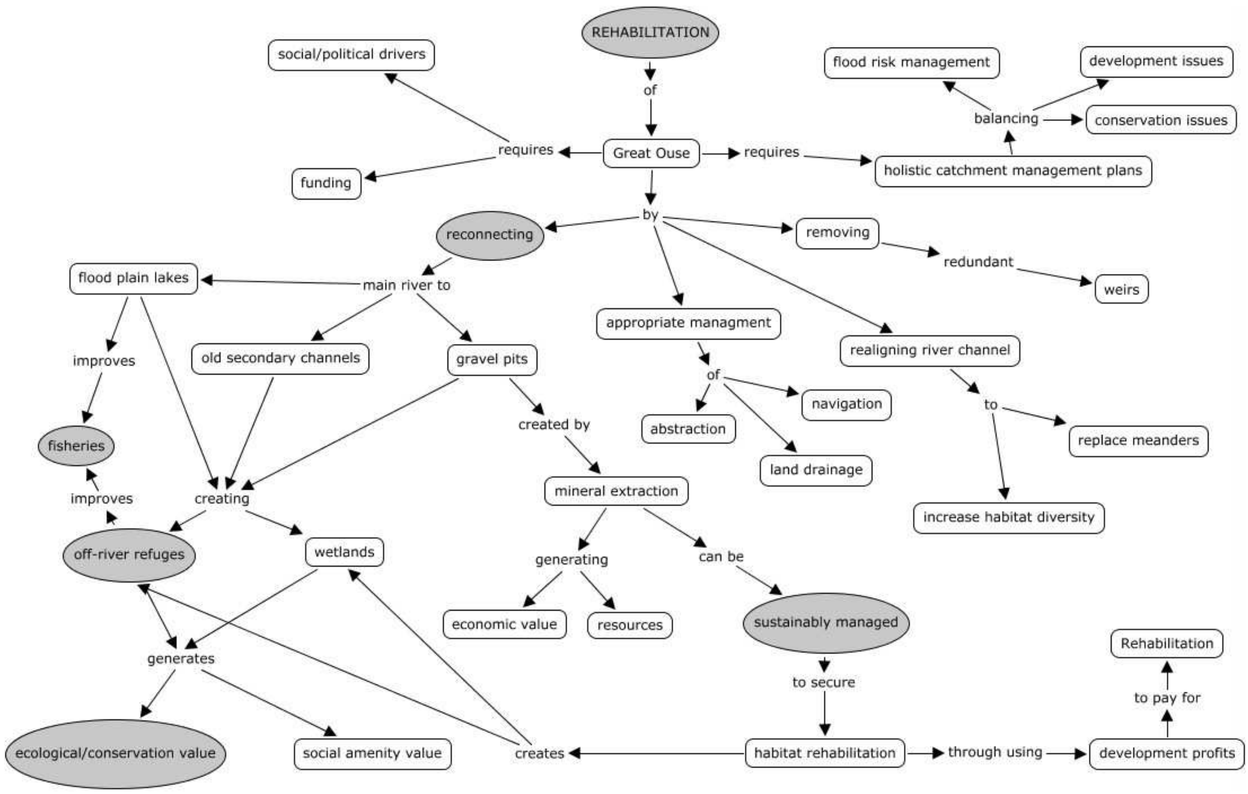


Figure 1.4 Concept map outlining the approach to rehabilitation of the Great Ouse lowland river system.

1.2 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.

1.3 Summary of modelling approach

The similarity of the concepts involved in the rehabilitation of both of the rivers considered allowed a common model to be developed for both systems. Both of the systems focused on the life cycle of a fish species and the interaction of life cycle processes with human influences on the quality of the habitats inhabited by the fish species. The common model integrated concepts regarding mortality, survival and recruitment processes for individual life stages within a species life cycle. Construction of a model around individual life stages allowed specific human activities and their influences over the quality of specific habitats to be considered. This is a common approach to evaluating the ecological status of fish species and their habitats, where key components of the causes of mortality are identified to allow rehabilitation efforts to be focused on critical bottlenecks within a species life cycle.

This report breaks down the QR model for the UK case study into; model primitives (Section 2), model fragments relating to specific processes and concepts (Section 3) and the integration of all these concepts into integrated scenarios that consider all life stages within the life cycle and their response to the rehabilitation of a particular habitat (Section 4). Within section 3 a number of small scenarios and simulations are used to present the model behaviour in relation to some of the specific processes and concepts involved. Exploration of the smaller concept-specific scenarios and simulations allow a greater and simpler understanding of the behaviours that may be found in the integrated scenarios.

All the scenarios developed from the common model are designed to show the effects that habitat rehabilitation can have to mitigate some of the negative effects human activities can have on river systems and the fish populations they support. A comparison of the two river systems within the model is considered in section 5.

2 Modelling primitives

2.1 Entities

Both the case studies were modelled using a single modelling approach which was built using a common set of entities. Within the model there are five primary entities; *Biological entity*, *Catchment*, *Habitat*, *Life stage*, *River* and *Set of entities* (Figure 2.1). The entity "Biological entity" is the super-type for all living component of the model and as such has sub-types of *Fish* and *Human*. The sub-types of Human include the relevant types of human groups active within the system (*General population*, *Stakeholder*, *Commercial user* and *Environment manager*). The entity *Catchment* is the landscape through which a river flows and in which the human activities occur. *Catchment* has two sub-types *Lowland catchment* and *Upland catchment*. The sub-types of the entity *Habitat* (*Floodplain*, *Juvenile habitat*, *Main channel* and *Spawning habitat*) are used to denote the different habitats within a river system that are used at different stages within a species life cycle. The species life cycle is represented by the entity *Life stage* and the sub-types *Adult*, *Egg*, *Juvenile* and *Sub Adult* (*Smolt* in the River Trent salmon model). The entity *River* comprises the three sub-types *Estuary*, *Lowland river* and *Upland river* to represent the different zones within a river system. The River Trent salmon model utilises both *Upland river* and *Lowland river* whereas the Great Ouse Bream model is only concerned with *Lowland river*.

The final entity "Set of entities" is used to denote entities that can be considered as group of individuals of a different entity. There are two sub-types for this entity:

1) *Population* – a specific group of individuals of a certain *Biological entity* and/or *Life stage*.
2) *Fishery* – a group of the entity *Angler*.

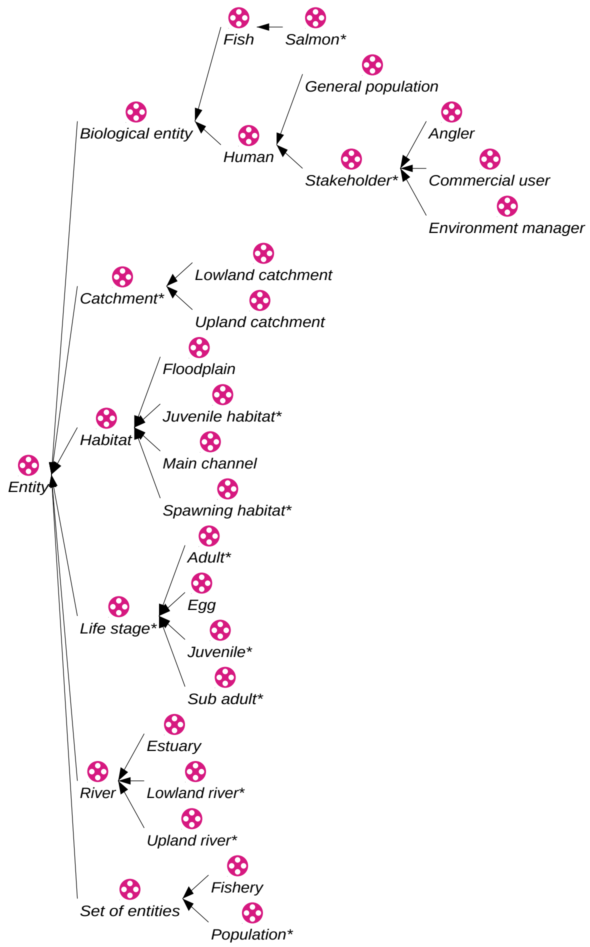


Figure 2.1 Entity hierarchy for the models built to explore the case study in the Rivers Trent.

2.2 Agents

Within the UK case studies the human activities which utilise the river and potentially degrade the environment, together with the human activities which improve the environment, are represented as agents within the model. The agents are group into two types, *Degradation agent* and *Rehabilitation agent* (Figure 2.2). *Degradation agents*, including *Agriculture*, *Water industry* and *River engineer*, utilise the *River* and the surrounding *Catchment* but their activity often acts to alter and degrade the quality of the *River*. *Rehabilitation agents*, including *Environmental manager* and *Fishery manager*, act to improve the ecological quality of the river and a fish population through rehabilitation of the river environment.

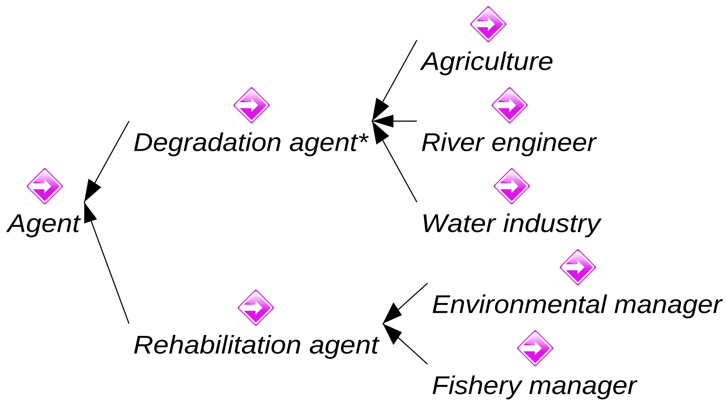


Figure 2.2 Agent hierarchy used for the UK case studies.

2.3 Configurations

The ten configurations used to relate entities and agents within the scenarios and model fragments of the UK case studies are described in Table 2.1. The configurations are used to link the life stages together into a life cycle and to relate a life stage to a particular habitat within a river system and the particular human activities that may be influencing the river habitat.

Table 2.1 Configurations used to relate entities and agents with the UK case studies.

Configuration	From (example)	To (example)	Comment
Consists of	*Population*	*Life stage*	Used to relate a population to the specific life stage it represents in the model
Exploits	*Fishery*	*Population (Adult)*	Used to represent the concept of a fishery acting on the adult life stage
Flows through	*River*	*Catchment*	The relation between the river channel and the surrounding landscape
Inhabits	*Population*	*River*	The occupation of a particular river type by a particular life stage
Manages	*Fishery manager*	*Fishery*	The control of a fishery by its managers
Occurs in	*Degradation agent*	*Catchment*	Relation between human activities and the landscape the river flows through
Part of	*Habitat*	*River*	Used to determine specific habitats within a river system
Recruits into	*Life stage* (*egg*)	*Life stage* (*Juvenile*)	Representation of the transition of individuals from one life stage to the next when life stages are represented by discrete populations
Rehabilitates	*Environmental manager*	*River*	The action of an environmental manager to improve habitat conditions
Stocks	*Fishery manager*	*Population* (*Juvenile*)	The addition of individuals to the juvenile life stage by a fishery manager – acting to enhance juvenile recruitment

2.4 Quantities and Quantity Spaces

The five quantity spaces used in the UK models are described in Table 2.2. Other than the rate quantity spaces (mzp) and activity quantity space (zp) all quantity spaces were designed as a five-class space from zero through an interval to a “medium” point value, through a second interval to a upper point value. This was done so that the quantity spaces could be easily related to each other in the modelling process.

Table 2.2 Quantity space definitions for the models used in the UK case studies.

Name	Spaces	Comment
Lsa	▪Zero, ━ Low, ▪Medium, ━Abundant, ▪Highly Abundant	Quantity space used to represent the numbers of individuals within a life stage
Mzp	━ Minus, ▪Zero, ━Plus	Quantity space used for calculated rates
Zlmgh	▪Zero, ━ Low, ▪Medium, ━Good, ▪High	Quantity space used to represent habitat qualities
Zlmhv	▪Zero, ━ Low, ▪Medium, ━High, ▪Very high	Quantity space used to represent intensities/extents of human activity and magnitudes of agents
Zp	▪Zero, ━ Plus	Quantity space used to represent occurrence of immigration and stocking

All the quantities used within the UK case studies modelling the Rivers Trent and Great Ouse are described in Table 2.3. There are five groups of quantities relating to *Life stages* or *Populations*, *Rivers* and *Habitats*, *Catchments* and *Degradation agents*, *Rehabilitation agents* and *Fisheries*.

Table 2.3 Quantities and their quantity spaces used in the UK case study QR model

Quantity	Quantity space	Comment
Life stages		
Number recruited	Lsa	The number of individuals entering a particular life stage having survived the previous life stage (or having been spawned)
Number surviving	Lsa	The number of individuals surviving a particular life stage, the number surviving results from mortality affecting the numbers that are recruited to the life stage
Net survival dynamic	Mzp	The combined influence of mortality and survival rates determining whether the number surviving is increasing, decreasing or static.
Population potential	Zlmhv	The maximum numbers of a life stage that can survive through the life stage based on the combination of numbers recruited and the habitat quality as limiting factors
Straying rate	Zp	The occurrence of immigration from a neighbouring population of adults – only relevant for salmon populations
River Habitats		
Habitat quality	Zlmgh	A general quantity relating to all rivers
Quality of juvenile habitat	Zlmgh	Specific habitat and specific river quality
Quality of spawning habitat	Zlmgh	Specific habitat and specific river quality
Quality of upstream connectivity	Zlmgh	The ability for adult salmon to migrate through the lowland river from the estuary to the upland spawning habitats. A low quality of connectivity represents numerous weirs with low passability impinging on the survival of adults to the spawning phase.
Abundance of floodplain waterbodies	Zlmhv	The quantity of connected back waters, lake and secondary channels in a lowland river floodplain
Catchments & Degradation		
Sedimentation level	Zlmhv	The amount of silt being eroded from the catchment into the upland river system
Abstraction level	Zlmhv	The intensity of activity of the water industry
Extent of flood defence	Zlmhv	The proportion of river isolated from the floodplain by flood levees
Extent of land drainage	Zlmhv	The proportion of the catchment that has been drained and converted from wetlands to agricultural land
Level of river engineering	Zlmhv	Extent of river channelisation, water regulation and dredging
Water abstracted	Zlmhv	Volume of water abstracted by the water industry
Value	Zlmhv	The value of an activity to human society representing both the economic revenue and potential aspects of human well being
Intensity	Zlmhv	The extent of a human activity within a catchment
Rehabilitation		
Rehabilitation rate	Zp	The activity of a type of rehabilitation
Extent of rehabilitation	Zlmhv	The amount of rehabilitation work undertaken
Resources used	Zlmhv	The cost of the rehabilitation work undertaken
Fishery		
Number of anglers	Zlmhv	
Exploitation rate	Mzp	The relationship between the number of anglers and the stock of adults available for capture
Stocking rate	Zp	The activity of a fishery manager stocking juveniles to enhance the numbers of juveniles recruited

2.5 Summary of model fragments and model assumptions

The common model developed for exploring the UK case study was built using 108 static model fragments; to describe the system structure, specify concepts and qualitative values in given circumstances; three process model fragments (Mf2, Mf18, Mf19) and 14 Agent fragments (Mf a1 to Mf a14) which describe the concepts related to human activities and their relationship with habitat quality. The 108 static fragments are structured around seven parent fragments (Mf1, Mf3, Mf4, Mf5, Mf8, Mf9 & Mf16), which relate to the concepts of life stages represented as populations (Mf1), rivers (Mf3), catchments, recruitment between life stages (Mf4), survival and mortality with a life stage (Mf5), catchments and habitat qualities (Mf8 and Mf9), and fisheries (Mf16). The content of the model fragments and the concepts of how they relater to the overall model are described in Section 3.

Seven modelling assumptions are used to limit the activity of certain model fragments to certain scenarios and simulations (Table 2.4). Firstly, the assumption label "Salmon model" is used in all scenarios that concern salmon, this is because certain model fragments, whilst containing elements common to both rivers being considered, should only apply to the salmon scenario in the River Trent. The other six assumption labels are related to the occurrence/non-occurrence of immigration and stocking and to the behaviour of a fishery and fisheries management within certain scenarios. These assumptions allow contrasting scenarios to be developed.

Table 2.4 Summary of assumption labels used in the River Trent and Great Ouse models.

Assumption label	Comment
Salmon model	Used to denote fragments that relate purely to the River Trent model (often for concepts regarding a lowland river).
Assume fishery growth in an under exploited fishery	Used to control the activity of Mf18. If this assumption is not used in a scenario in which a fishery occurs then the number of anglers set in the scenario will not alter though the scenario. If the assumption is used then the fishery should increase in size in a situation where the exploitation rate is "minus"
Fisheries management controls exploitation	Used to control the activity of Mf a10 and the control of a fishery manager over the level of exploitation.
Immigration active	Controls whether adult recruitment is supported by immigration from a neighbouring population – Immigration active means the numbers of adults recruited is enhanced.
No Immigration	Controls whether adult recruitment is supported by immigration from a neighbouring population – no immigration means number of adults recruited equals the number of sub-adults surviving.
No stocking of young juveniles	Controls whether juvenile recruitment is enhanced by stocking by a fishery manager – no stocking means juvenile recruitment is limited by the survival of eggs.
Stocking active	Controls whether juvenile recruitment is enhanced by stocking by a fishery manager – stocking active means juvenile recruitment is enhanced.

3 GENERAL SCENARIO STRUCTURE AND MODELLING CONCEPTS

3.1 General model scenarios

The whole scenario of the UK case studies 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 Salmon model the life cycle in 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 in 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 (Figure 3.1).

In the scenario the egg, juvenile and adult life stage has one degradation agent and one rehabilitation agent. The degradation agent is related to the catchment where as the rehabilitation agent is linked to the specific river for that life stage.

1) Egg – the effects of Agriculture on sedimentation within the catchment and spawning habitat quality versus the habitat rehabilitation by the action of an Environmental manager undertaking gravel cleaning.
2) Juvenile – the effects of abstraction by the water industry on habitat quality and the rehabilitation effects of an environmental manager undertaking habitat improvement schemes.
3) Adult – the effect of River engineering on the connectivity of the lowland river versus the actions undertaken by environmental management to restore connectivity (e.g. fish pass construction and weir removal).

Additionally within the River Trent salmon model a *Fishery* is considered which exploits the adult population. Given the occurrence of a fishery the effects of a fishery manager can be considered within the scenario. The fishery manager can affect the scenario through both stocking of juveniles, to enhance juvenile recruitment, and management of the fishery to regulate the fishing effort and the exploitation of the adult population.

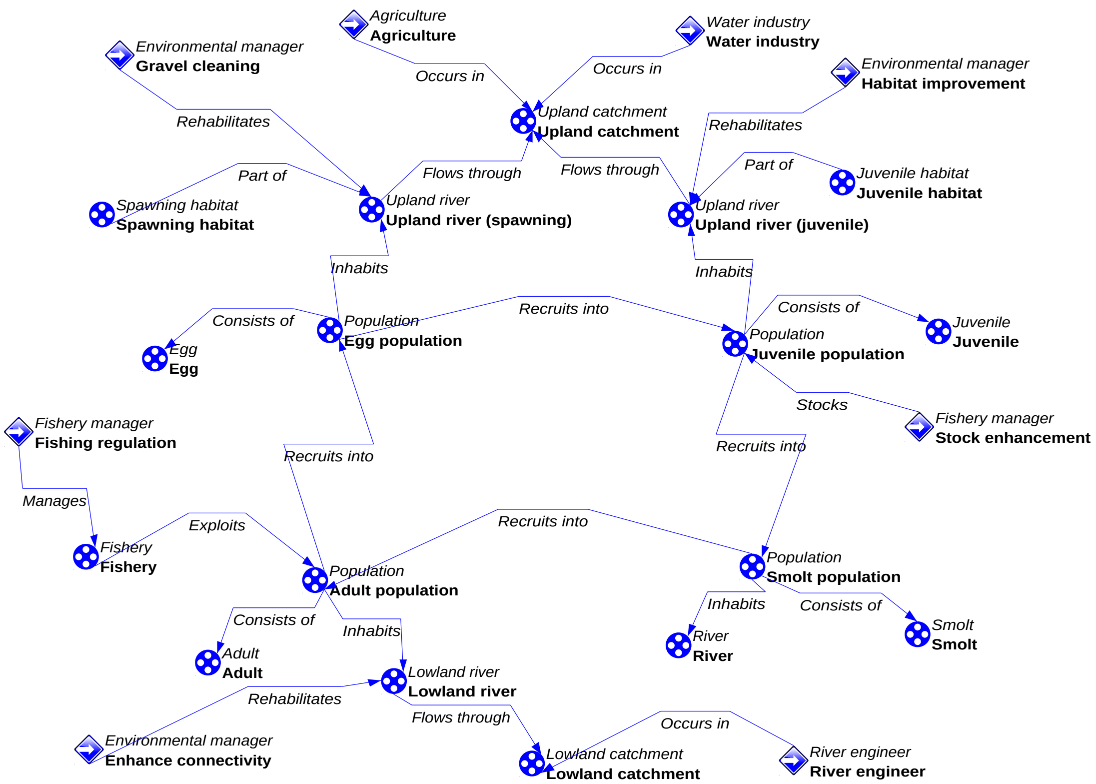


Figure 3.1 The generic structure of the salmon life cycle model used in the River Trent case study, showing configurations between all relevant entities and agents for all life stages.

The general scenario used in the River Great Ouse case study also follows the life cycle approach of adult-egg-juvenile-sub adult-adult (Figure 3.2). The term "smolt" is specific to migratory salmonids so in the bream model a life stage "sub adult" is used to represent the period between young juveniles and mature adults. This general scenario differs to that of the salmon model in that all life stages inhabit different habitats within the *Lowland river* and the *Lowland catchment*.

1) Juvenile population – inhabits the juvenile habitats in the marginal zone of the lowland river. The quality of the juvenile habitats is determined by the effect of flood defence measures altering riparian habitat and the action of environmental managers rehabilitating the riparian habitat.
2) Sub adult population – inhabits the *Main channel* of the lowland river. The quality of this habitat is affected by channelisation and regulation of the main river by a *River engineer.* Habitat quality is improved by the actions of an Environmental manager.
3) Adult population – inhabits the backwater habitats (connected floodplain lakes) of the lowland river. Extensive land drainage (often due to Agriculture) removes or disconnects floodplain lakes. These lakes can be recreated (e.g. gravel pit lakes) or reconnected by the action of an environmental manager.

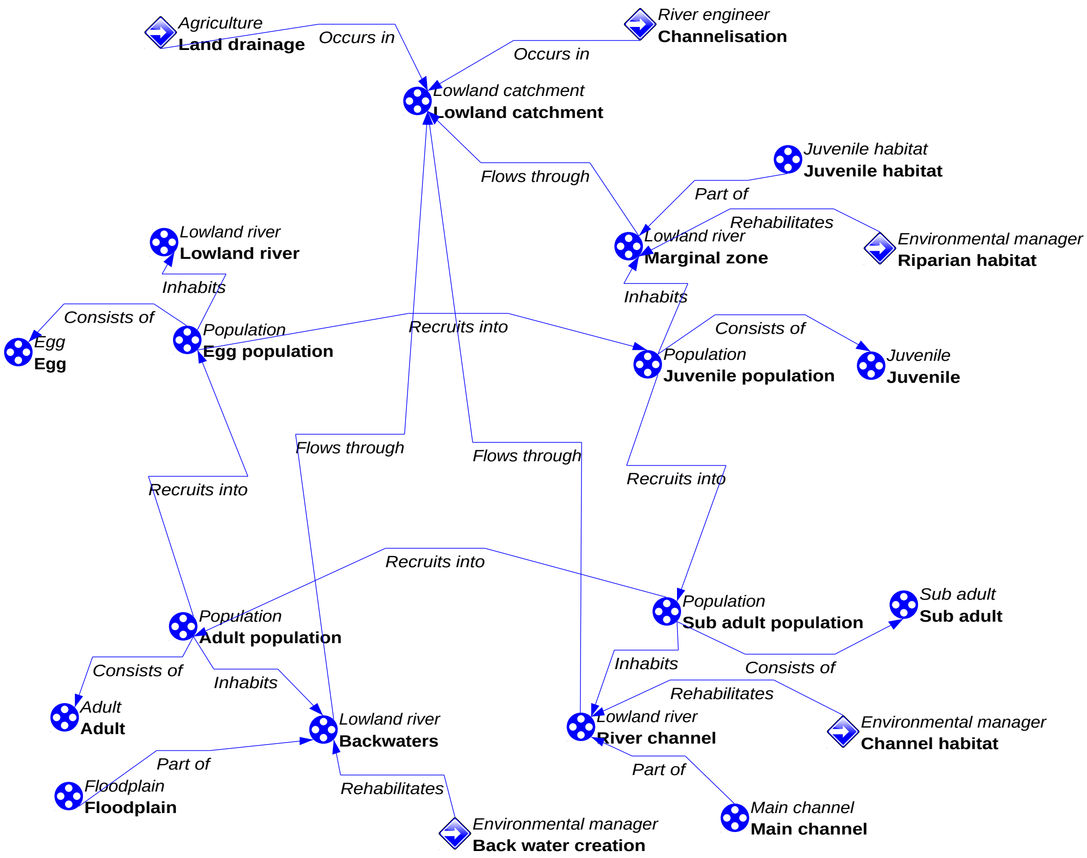


Figure 3.2 The generic structure of the bream life cycle model used in the River Great Ouse case study, showing configurations between all relevant entities and agents for all life stages.

3.2 Modelling concepts

This section breaks down the generic scenarios into specific modelling concepts that are used to describe key processes and stages within the model. These are grouped into life stages (Section 3.2.1); rivers, catchments, habitats and habitat quality (Section 3.2.2); life stage mortality and survival (Section 3.2.3); life stages and recruitment (Section 3.2.4); stocking and immigration (Section 3.2.5); human activities (Section 3.2.6) and fishery (Section 3.2.6). In each section the relevant model fragments, test scenarios, simulations and behaviours are described.

3.2.1 Life stages

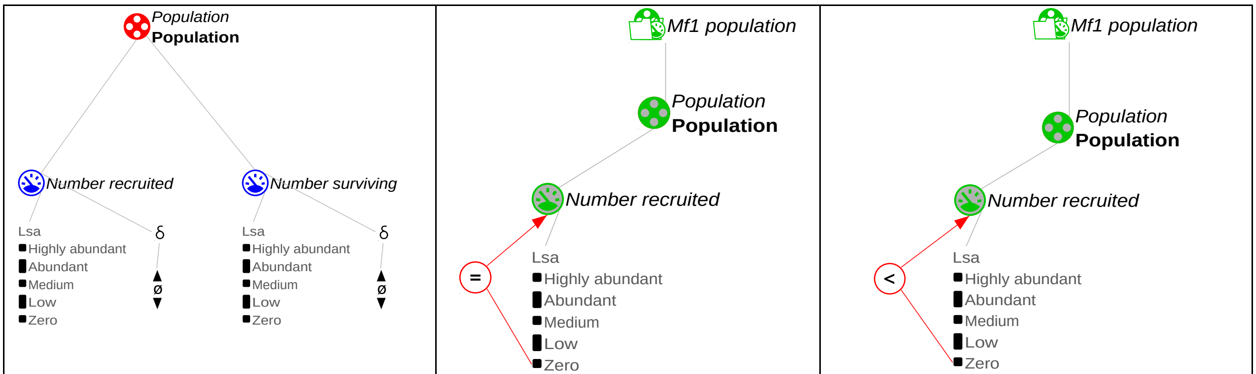
Initial concepts and modelling approach

The initial formulation for representation of life stages within a life cycle was for each life stage to be represented as a specific quantity e.g. Number of adults (Noble & Cowx 2006). However, in order to use single model fragments that represent concepts and characteristics that are common to all life stage, each life stage was considered to be an individual population. In this way single model fragments could be built that apply to all life stages/populations. This approach also allowed the life cycle to be modelled in an approach that specifically considered the transition of individuals within (survival/mortality, Section 3.2.3) and between (maturation and recruitment, Section 3.2.4) life stages. Early modelling attempts used only a single “Number of” quantity to describe the abundance of the population/life stage. However, only have a single quantity made it very difficult to model the abundance of the life stage when subject to different levels of recruitment from the previous life stage and different levels of mortality within a life stage (see Section 3.2.3 for initial attempts to model mortality and recruitment). Therefore, an alternative modelling approach was used which focussed on the survival/mortality within a life stage. The final modelling approach considered that, with each life stage represented as a population, each life stage would have a certain number of individuals entering the life stage from the previous stage – the *Number recruited*. Those recruited individuals would then be subject to a mortality rate within the life stage and only a certain proportion would survive the life stage – the *Number surviving*. Having the numbers recruited and surviving for each life stage means that the number of life stages planned for the model (Noble & Cowx 2006) could be reduced, with returning adults and spawning adults being merged into a single adult life stage (i.e. Number recruited is equivalent to returning adults and Number surviving equates to the number of adults spawning). Whilst the quantity spaces are the same for both numbers recruited and numbers surviving, and they are qualitatively the same, they are not considered quantitatively equal. The model concept considers that there is always mortality within a life stage, so that a highly abundant number recruited is quantitatively larger than a highly abundant number surviving but that they are qualitatively equivalent. Therefore, at a normal level of mortality in high quality habitat (see section 3.2.2) then a highly abundant number of individuals can survive if a highly abundant number of individuals are recruited.

Final modelling implementation

The key entities within the life cycle are the different life stages and the survival of an individual from one life stage to the next. 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 three model fragments; “Mf1 population” and its two child fragments “Mf1a recruitment doesn’t exist” and Mf1b recruitment exists”. In Mf1 if there is a *Population* then the quantities *Number recruited* and *Number surviving* are introduced for that population. Mf’s 1a and 1b then introduce the concepts of the Number recruited being greater than (Mf1b) or equal to (Mf1a) zero (Figure 3.3).

These model fragments can be related to specific life stages using the life stage entities and the “*Consists of*” configuration e.g. *Population – Consists of – Juvenile*.



Mf1	Mf1a	Mf1b

Figure 3.3 Model fragments 1, 1a and 1b relating to the concepts of a life stage being represented as a population.

3.2.2 Rivers, Catchments, Habitats and Habitat Quality

Rivers, *Habitat*s and *Habitat Quality* are represented using six model fragments including the generic parent fragment "Mf3 river". The structure of these fragments allows specific habitat types and qualities of specific habitats to be related to a generic habitat quality of a generic river. This allows models to be constructed from a set of common model fragments (Figure 3.4). In the generic river model fragment Mf3 if a *River* exists then the quantity *Habitat quality* is introduced for this river. Model fragment 3a describes the specific situation for salmonid spawning habitats (specifically ascribed for the River Trent model using the "Salmon model" assumption label). In Mf3a if *Spawning habitat* is *Part of* the *River* then the quantity "*Quality of spawning gravels*" is introduced and this is related to the general *Habitat quality* by P+ (*Quality of spawning gravels*, *Habitat quality*) and a full quantity space correspondence. Model fragment 3c has a similar structure except it denotes *Juvenile habitat* and *Quality of juvenile habitat*.

Model fragment 3b was built to be a parent fragment for *Lowland river* instances and adds in *Lowland river* as a conditional entity and makes a relation between *Lowland river* and *River* to denote that they are the same in that instance. Model fragment 3d is a child of Mf3b and specifies instances when *Floodplain* is the *Part of* the *Lowland river* being considered. In instances when *Floodplain* habitat occurs (conditional entity) then the "*Abundance of floodplain waterbodies*" is added as a quantity of the river. In this instance there is a P+ relation (*Abundance of floodplain waterbodies*, *Habitat quality*) and a full directed correspondence between their quantity spaces.

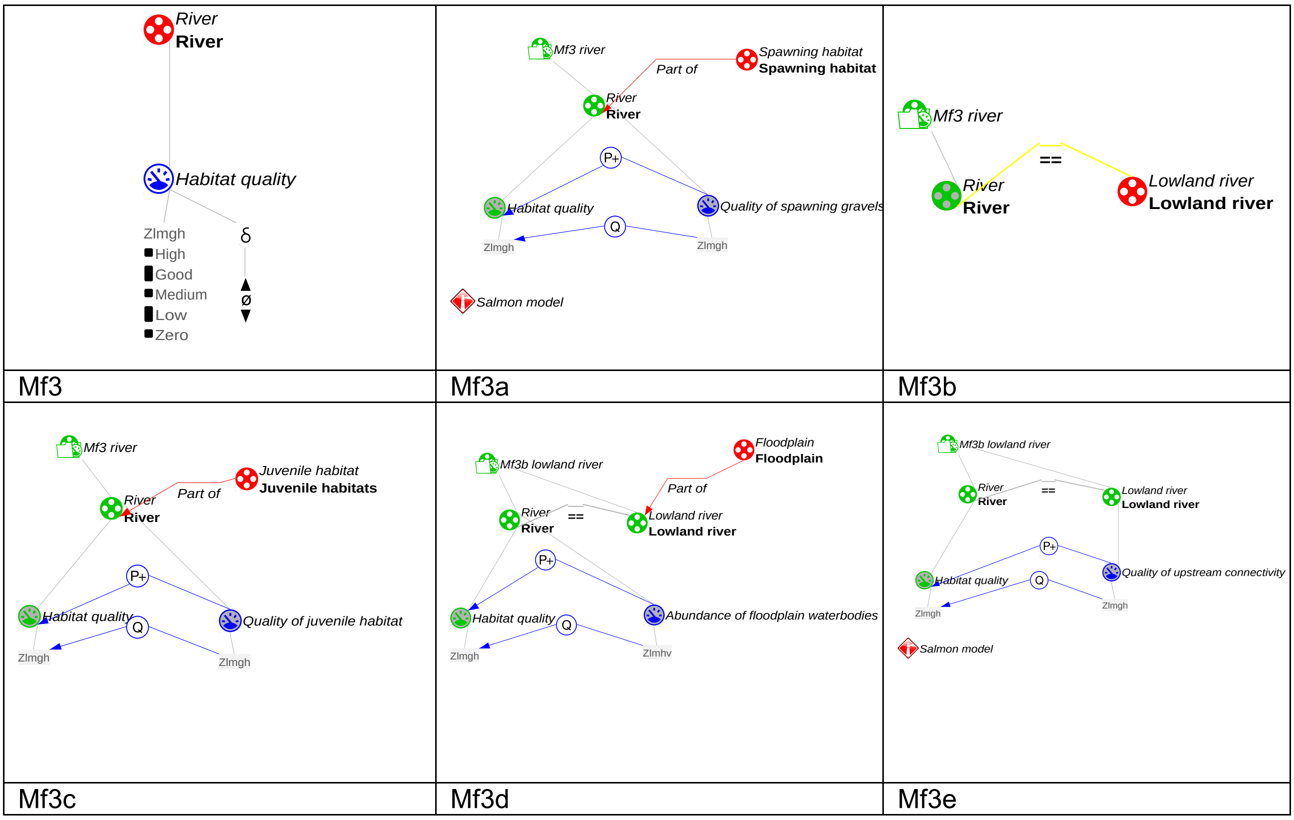


Figure 3.4 Model fragments used to describe rivers, habitats and habitat quality in the UK case study.

Model fragment 3e is a specific fragment for the *Lowland river* in the River Trent salmon model (denoted using the "Salmon model" assumption label). When a lowland river is considered in the salmon model then it is the connectivity of the river channel that is considered to control the habitat model for the migrating adult salmon. Therefore, when Mf3e is active then "*Quality of upstream connectivity*" is added as a quantity to *Lowland river* and there is a P+ relation and directed quantity space correspondence between the quantities (*Quality of upstream connectivity*, *Habitat quality*).

River and *Catchment* are used as entities to specify the specific zones of a river and to provide an interface between human activities and the river and its habitat quality. Therefore, two basic model fragments Mf8 Upland catchment and Mf9 Lowland catchment were created as parent fragments for use in construction of the fragments describing the control of habitat quality (see Section 3.2.6). These fragments link the river entities to their related catchment entities using the Flows through configuration (Figure 3.5)

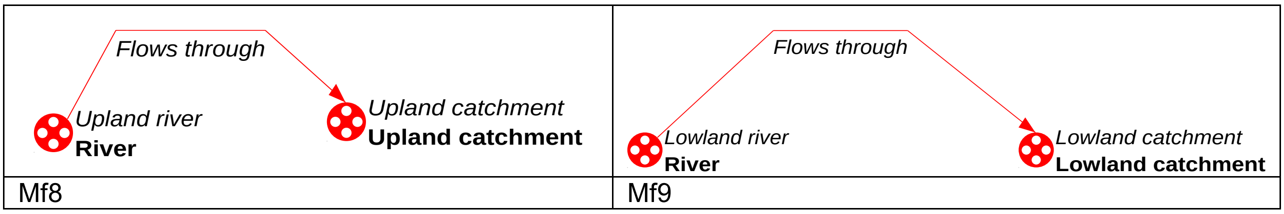


Figure 3.5 Model fragments used to describe rivers and catchments in the UK case study.

3.2.3 Life stages and mortality/survival

Initial concepts and modelling approach

The life cycle focus of the two case studies looks at the effects of human activity on the quality of river habitats and the knock on effects on the mortality/survival of individuals in a population. The model describes that each life stage inhabits a specific habitat and that the size of the life stage population and its survival can be related to the quality of that habitat and the size of the population of the previous life stage (recruitment). The initial modelling concept considered that each life stage would be subject to a mortality rate and a recruitment rate (survival from previous life stage). The size of each population would then be controlled by these two competing rates. An early attempt at implementing this in a model fragment is shown in Figure 3.6.

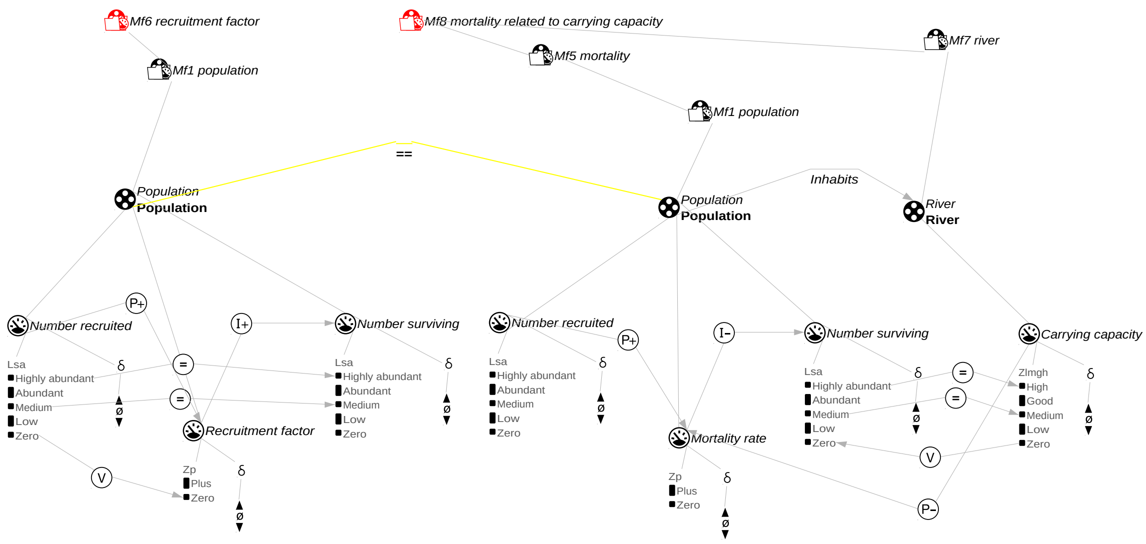


Figure 3.6 A model fragment showing an early version of the implementation of competing recruitment and mortality rates.

The implementation shown above attempted to model a recruitment rate (recruitment factor) and a mortality rate that were always active when a population exists (*Number recruited* >zero). The rates would then be either in or out of balance depending on the relative sizes of *Numbers recruited* to *Numbers surviving* and *Numbers surviving* to the *Carrying capacity* of the River (representing an aspect of habitat quality i.e. the size of population that that river could support). This implementation attempted to represent that mortality, survival and recruitment are never zero (unless the population is extinct) and that the size of the population only changes when mortality is greater or less than the level of recruitment. The implementation also attempted to represent that the numbers surviving are limited by both the habitat quality (through mortality) and by the level of recruitment. In this implementation an attempt was made to control the balance of the I+ relationship *Recruitment factor*, *Number surviving* and the I- relationship *Mortality rate*, *Number surviving*. The balance was determined using child fragments to specify relative sizes of mortality and recruitment based on the relative sizes of the population numbers and the carrying capacity. However, this implementation did not work because simulations required the system to shift from a state where mortality rate and recruitment rate were in equilibrium to a state where they were in imbalance back to a state of equilibrium. This return to equilibrium was impossible to model once the relative magnitudes of the two rates had been altered.

Given the difficulty of modelling competing rates acting on a single quantity an alternative solution was considered. This solution implemented the following concepts:

1) The *Numbers surviving* are limited by either or both of the *Numbers recruited* and the *Habitat quality* (whichever is lesser) – the size limit of the *Numbers surviving* 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 the 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*. A couple of approaches to model *Population potential* were considered, one with the potential being a calculation between *Numbers recruited* and Habitat quality (Figure 3.7) and one using value correspondences between the controlling variable and the potential (where the controlling quantity was the quantity with the lesser magnitude).

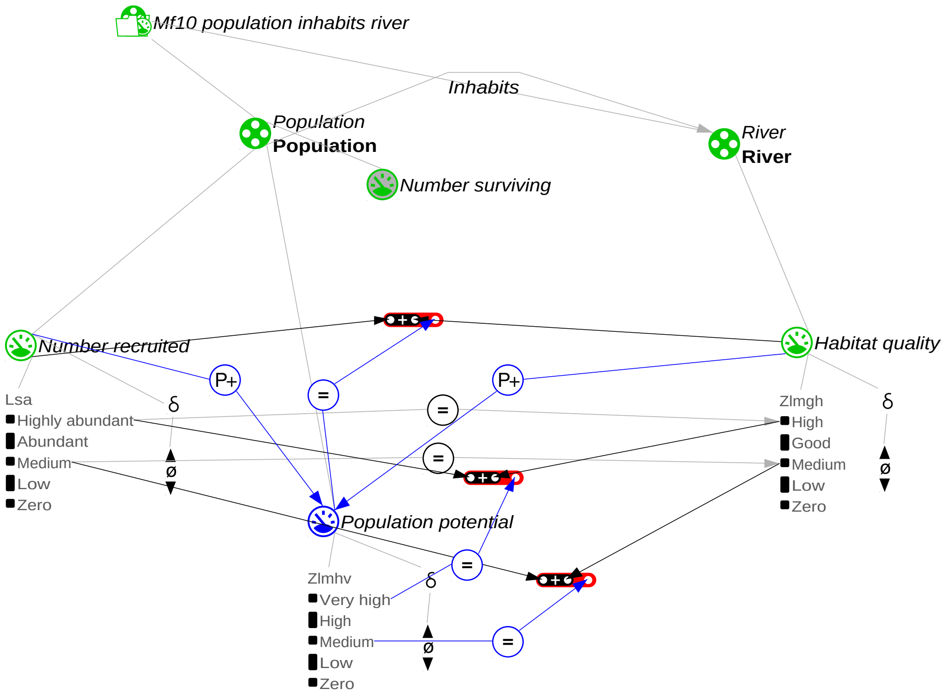


Figure 3.7 Alternative implementation attempt for derivation of the *Population potential* from the *Numbers recruited* and the *Habitat quality*.

The use of the addition calculus to determine the *Population potential* proved difficult for a number of reasons. Firstly, the potential could only be zero when both *Number recruited* and *Habitat quality* were zero – conceptually the *Population potential* should be zero when it is limited by either quantity being zero. Secondly, some of the calculations leave ambiguous magnitude results for the *Population potential*. Thirdly, the calculus leaves ambiguities for the derivative of *Population potential* when *Numbers recruited* and *Habitat quality* have conflicting derivatives. The implementation using the correspondences was therefore used in the final model.

Final modelling implementation

The model fragments described here model the process of survival and mortality through the course of one life stage, this is modelled as the relation between the *Numbers recruited* (the numbers of individuals at the start of the life stage) and the *Numbers surviving* at the end of the life stage. The modelling concept used here is that the *Numbers surviving* are limited by firstly the original *Numbers recruited* and secondly by the *Habitat quality* of the *River* they inhabit. Therefore, *Number recruited* and *Habitat qualities* were modelled as limiting factors for the *Numbers surviving*. The modelling process for this used four main model fragments (Figure 3.8). Mf5 related Mf1 population to Mf3 river using a *Population - Inhabits - River* configuration. Equalities are then used to relate the point values of the quantity spaces of

Number recruited and *Habitat quality* to denote that *Highly abundant* has a qualitative equality with High habitat quality (also medium equals medium). This denotes the concept that High habitat quality can support Highly abundant populations but medium habitat quality can only support medium numbers of individuals. This concept of limiting factors is combined into the quantity *Population potential* which indicates the maximum numbers that could survive given the Numbers recruited and the prevailing Habitat quality. The quantity *Population potential* is assigned by Mf6 to any population as a consequence of Mf5 being active. The value of *Population potential* is calculated using the suite of child model fragments Mf6a to Mf6j (Figures 3.9 and 3.10). The ten child fragments model the situation so that at any point *Population potential* is set and controlled by which ever is lesser of *Numbers recruited* or *Habitat quality*. Full descriptions of these model fragments are given in Table 3.1.

Mf2 is a process fragment that adds in the quantity *Net survival dynamic* as a consequence of a population occurring. The quantity *Net survival dynamic* represents the balance between survival and mortality processes and has an I+ relation (*Net survival dynamic*, *Numbers surviving*). *Net survival dynamic* has an mzp quantity space where the value plus indicates that survival is greater than mortality, minus indicates that mortality exceeds survival and the zero value indicates that survival and mortality processes are in balance (i.e. numbers surviving matches the population potential). In Mf7 the value for Net survival dynamic is calculated using a calculus subtraction "*Population potential* minus *Number surviving*". For the calculation to be modelled correctly equality statements are made between the point values of the quantity spaces of *Population potential* and *Numbers surviving* and two proportionalities are specified P+ (*Population potential*, *Net survival dynamic*) and P- (*Numbers surviving*, *Net survival dynamic*).

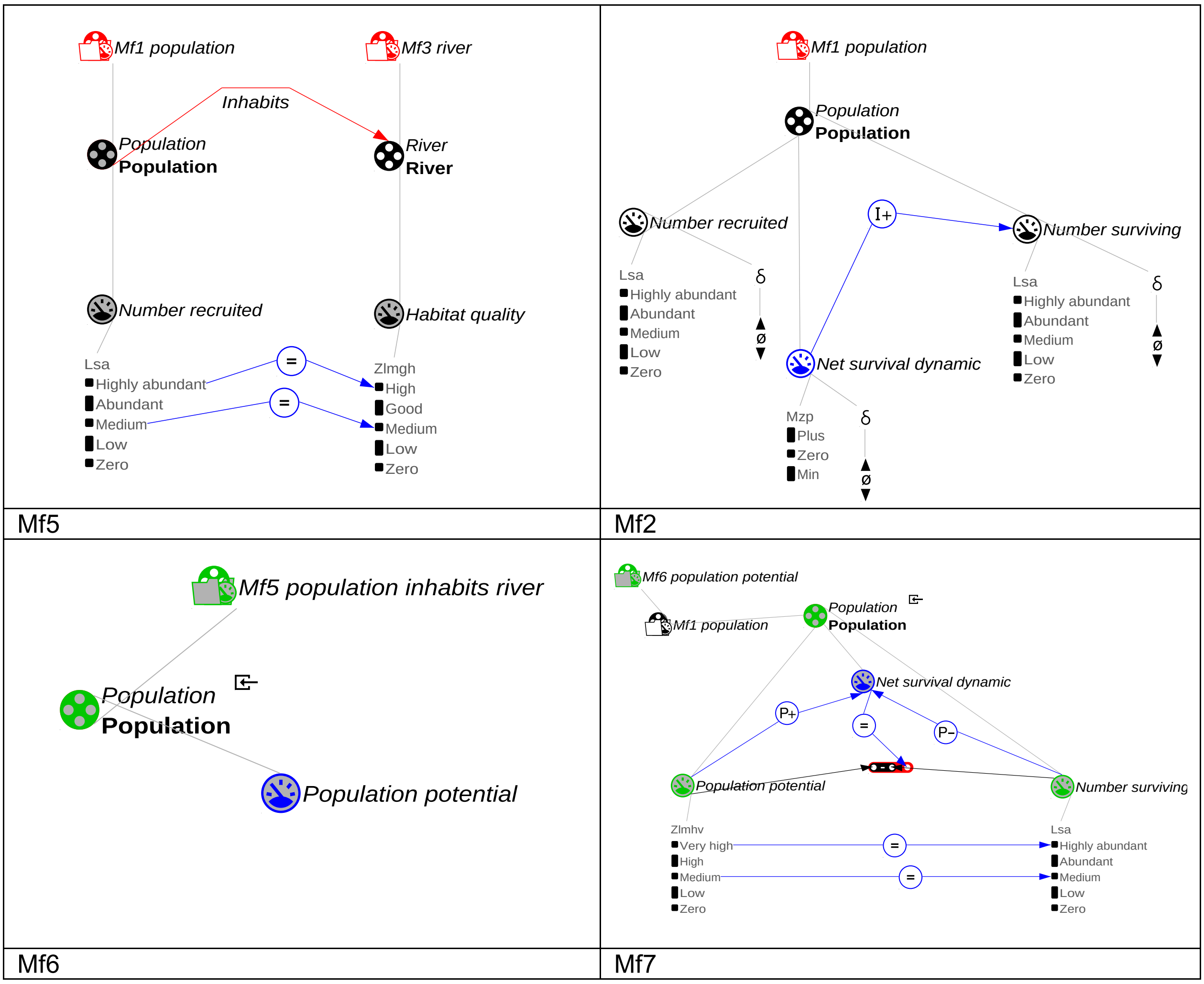


Figure 3.8 Model fragments 5, 2, 6, and 7 used to model life stage survival/mortality processes in the UK case study.

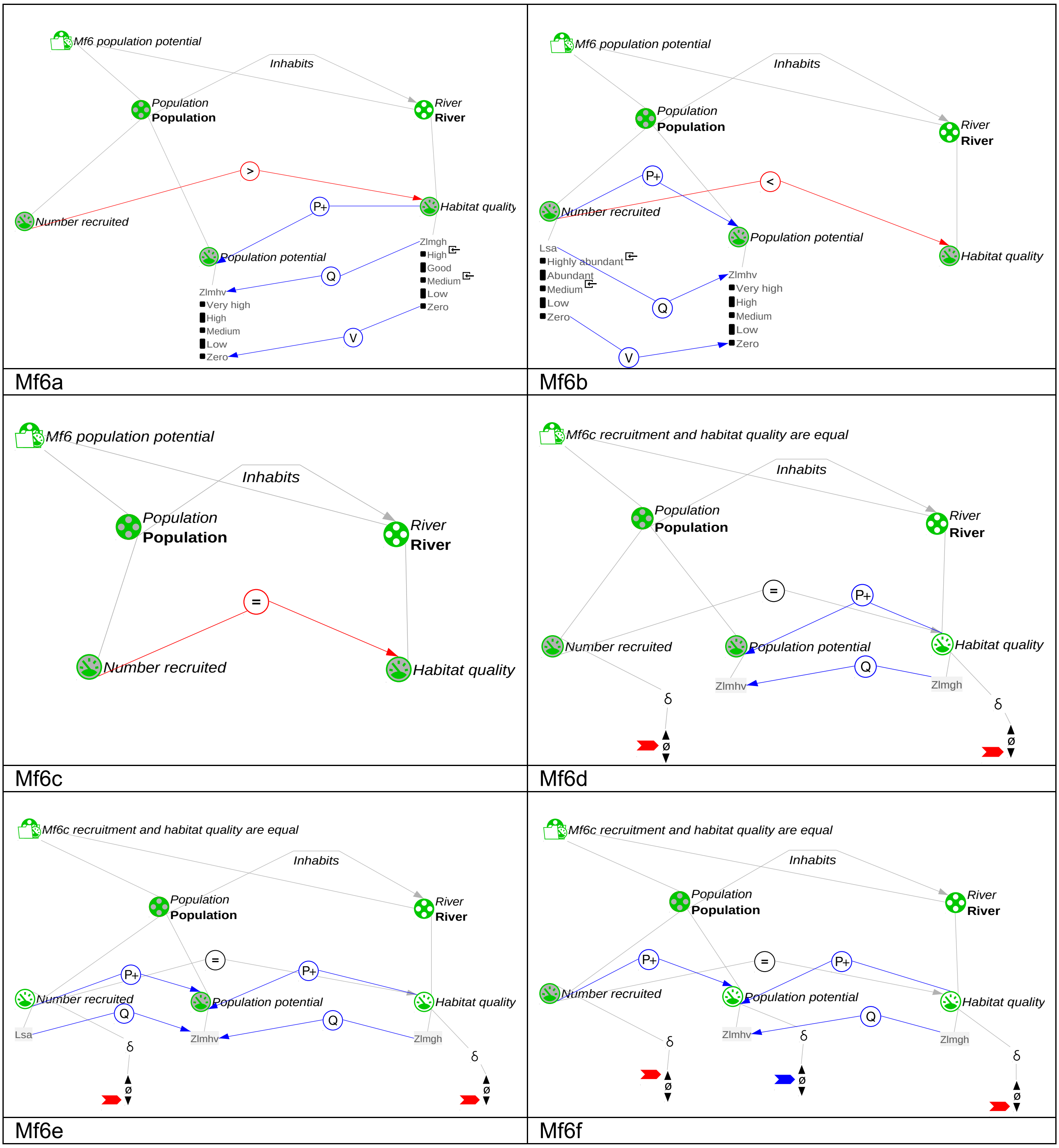


Figure 3.9 Model fragments 6a to 6f used to model population potential for life stage survival/mortality processes in the UK case study.

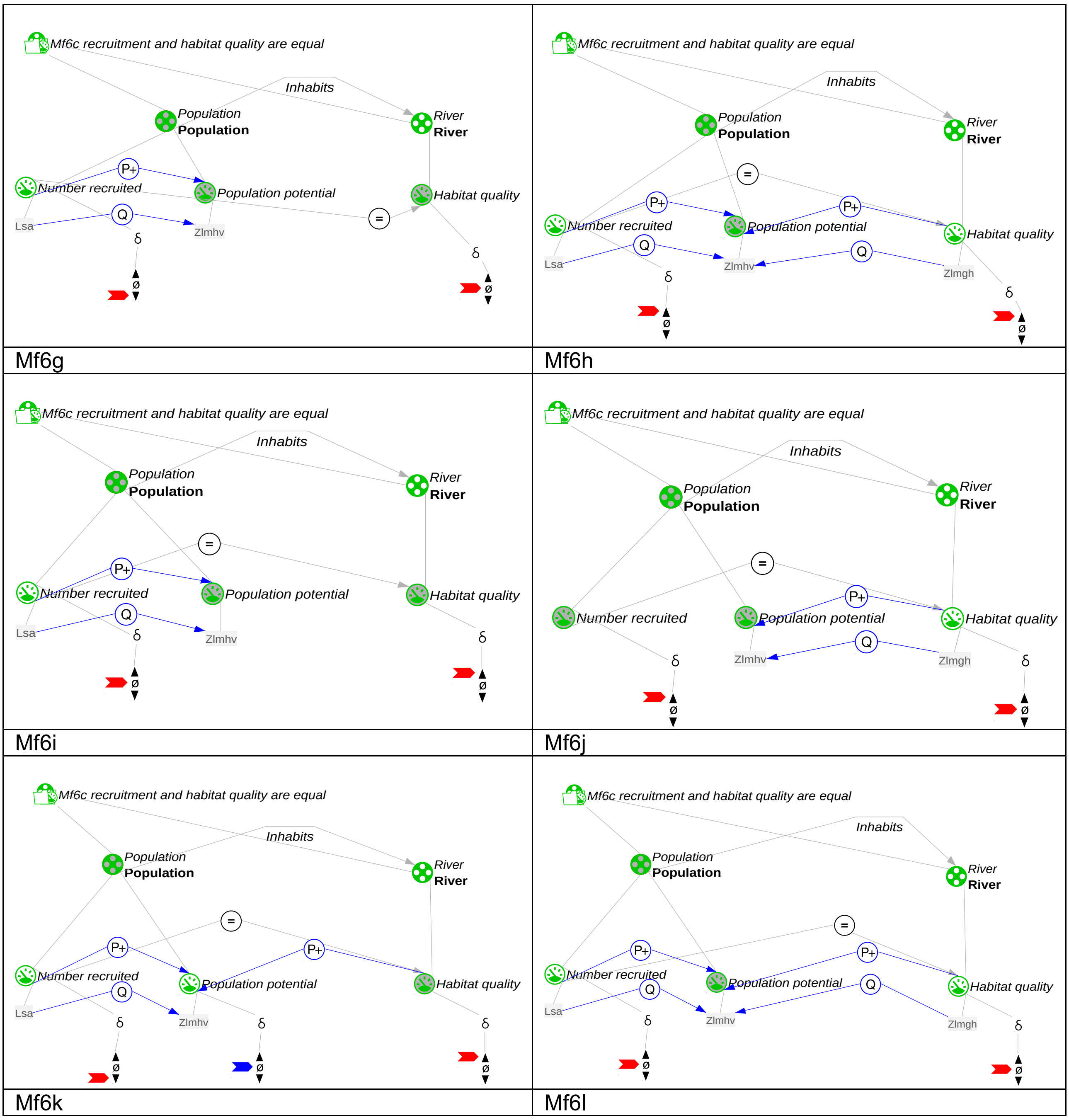


Figure 3.10 Model fragments 6a to 6l used to model population potential for life stage survival/mortality processes in the UK case study.

This modelling set up allows the *Number surviving* to respond to changes in the *Population potential* using a conceptual balance/imbalance in mortality and survival, when the *Population potential* is adjusted by changes in the levels of recruitment and the prevailing habitat quality for each life stage.

Table 3.1 Textual explanation of model fragments 6a to 6j controlling the value of Population potential based on the Number recruited and the Habitat quality.

Model fragment	Concept (conditions and consequences)
Mf6a	Habitat quality is less than recruitment and sets the limit for Population potential IF Habitat quality is less than Numbers recruited THEN: P+ relation habitat quality, population potential Quantity space correspondence Habitat quality, Population potential Value correspondence Habitat quality = Zero, Population potential = Zero
Mf6b	Number recruited is less than Habitat quality and sets the limit for Population potential IF Number recruited is less than Habitat quality THEN: P+ relation Number recruited, population potential Quantity space correspondence Number recruited, Population potential Value correspondence Number recruited = Zero, Population potential = Zero
Mf6c	Number recruited is equal to Habitat quality and both set the limit for Population potential Number recruited is equal to Habitat quality: P+ relation Number recruited, population potential P+ relation Habitat quality, population potential Parent fragment for Mf6d to Mf6l
Mf6d	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δø AND Habitat quality δ- THEN: Directed full quantity space correspondence Habitat quality, Population potential P+ relation Habitat quality, population potential
Mf6e	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δ- AND Habitat quality δ- THEN: Directed full quantity space correspondence Habitat quality, Population potential Directed full quantity space correspondence Numbers recruited, Population potential P+ relation Number recruited, population potential P+ relation Habitat quality, population potential
Mf6f	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δ+ AND Habitat quality δ- THEN: Directed full quantity space correspondence Habitat quality, Population potential P+ relation Number recruited, population potential P+ relation Habitat quality, population potential Population potential δø
Mf6g	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δ- AND Habitat quality δø THEN: Directed full quantity space correspondence Number recruited, Population potential P+ relation Number recruited, population potential
Mf6h	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δ+ AND Habitat quality δ+ THEN: Directed full quantity space correspondence Habitat quality, Population potential Directed full quantity space correspondence Number recruited, Population potential P+ relation Number recruited, population potential P+ relation Habitat quality, population potential
Mf6i	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δø AND Habitat quality δ+ THEN: Directed full quantity space correspondence Number recruited, Population potential P+ relation Number recruited, population potential
Mf6j	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δ+ AND Habitat quality δø THEN: Directed full quantity space correspondence Habitat quality, Population potential P+ relation Habitat quality, population potential
Mf6k	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δ- AND Habitat quality δ+ THEN: Directed full quantity space correspondence Habitat quality, Population potential P+ relation Number recruited, population potential P+ relation Habitat quality, population potential Population potential δø
Mf6l	Number recruited is equal to Habitat quality and both set the limit for Population potential IF Number recruited is equal to Habitat quality AND Number recruited δø AND Habitat quality δø THEN: Directed full quantity space correspondence Habitat quality, Population potential Directed full quantity space correspondence Number recruited, Population potential P+ relation Number recruited, population potential P+ relation Habitat quality, population potential

Test scenarios – e.g. "Test S7 Numbers recruited increase from zero whilst Habitat quality is medium and steady"

A number of test scenarios (Test S1 to Test S10) were developed to test the behaviour of a single population/life stage in response to a range of values and behaviours of recruitment and habitat quality. These were used to ensure that the simulations gave the correct behaviours for the survival within a particular life stage. Scenario "Test S7 Numbers recruited increase from zero whilst Habitat quality is medium and steady" is shown as an example here. In this scenario the expected behaviour is that *Population potential* and *Numbers surviving* are initially zero because *Number recruited* is zero. As *Number recruited* increases (exogenous behaviour) the *Population potential* and *Numbers surviving* increase until *Number recruited* and *Population Potential* are equal to the *Habitat quality* when the *Population potential* and *Numbers surviving* remain at medium, limited by *Habitat quality* which is medium and steady (exogenous). The scenario, dependency diagram, behaviour path and value history for the expected behaviour in this scenario is presented in Figure 3.11.

Table 3.2 Summary of behaviour for the scenario "Numbers recruited increase from zero whilst Habitat quality is medium and steady".

Scenario Name	Numbers recruited increase from zero whilst Habitat quality is medium and steady
Full simulation	13 states
Initial States	[1]
End states	[9, **11**] End state [11] is the correct end state
Relevant behaviour path	[1, 2, 4, 7, 10, 11] Any path from [1] to [11]
Behaviour description	Due to the Number recruited being zero and having and exogenous increase the Population potential starts as zero and increasing [1]. Whilst Number recruited remains less that Habitat quality Population potential matches the increase e.g. [2] and [4]. In state [2] Number surviving is less than Population potential so net survival dynamic is plus causing Numbers surviving increase. This pattern continues until Number recruited is equal to or greater than Habitat quality when population potential becomes medium and steady limited by the Habitat quality. The correct end state for this behaviour is when Number recruited is High and steady, Number surviving is medium and steady, Population potential is medium and steady and Net survival dynamic is zero and steady. The different valid paths from [1] to [11] reflect the potential for Number surviving to increase to the Population potential at different rates. **NOTE** Paths to end state [9] indicate an erroneous behaviour that can't be solved due to inconsistencies regarding the value and derivative for Net survival dynamic.

Following the example shown in Figure 3.11 and Table 3.2, most of the test scenarios indicated that the model fragment configuration as described above did not adequately describe the predicted behaviour. Whilst the predicted behaviours were often present there were often additional erroneous behaviours and incorrect end-states. Therefore a modelling solution was sought to eradicate the erroneous behaviour paths and end states.

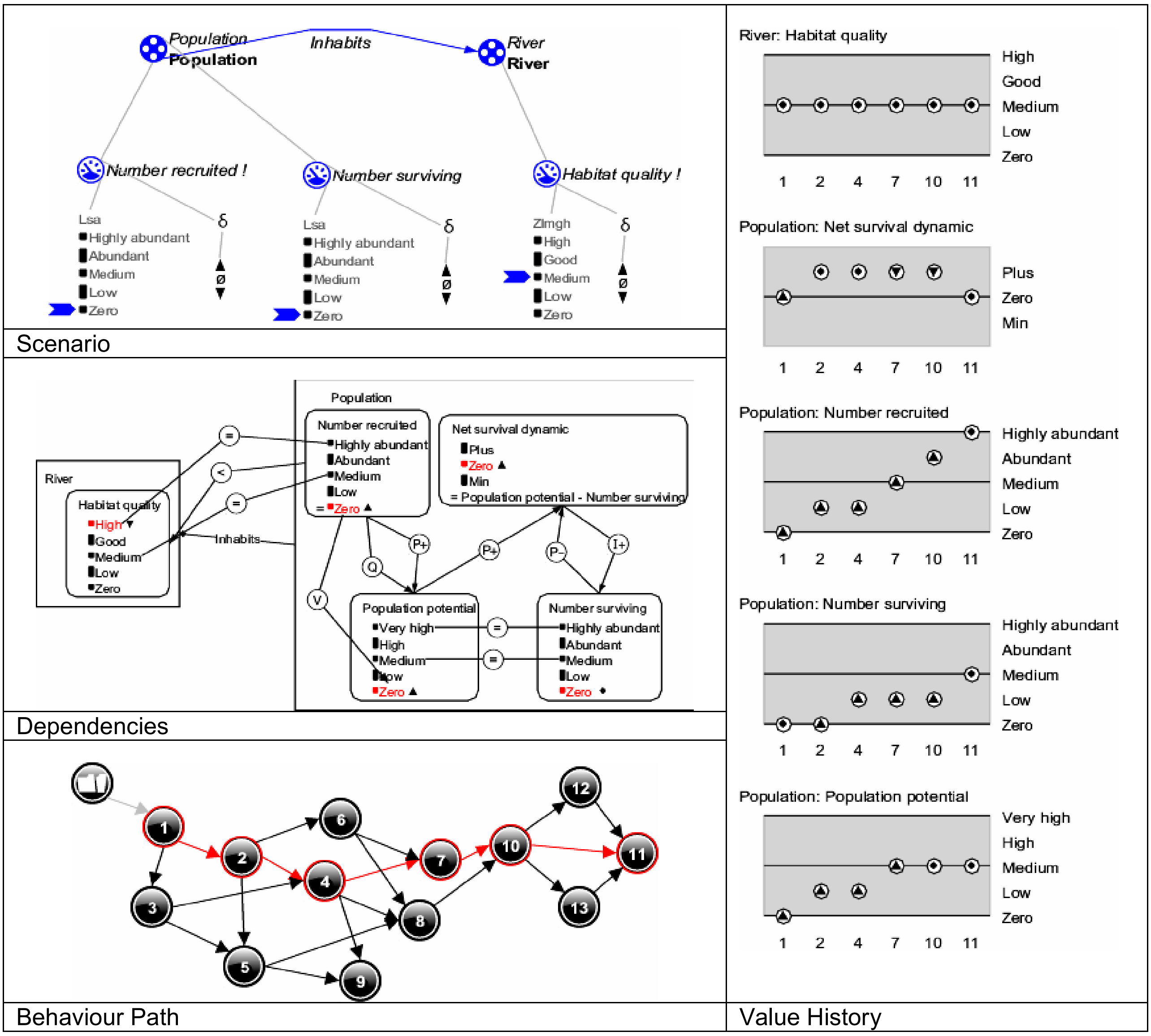


Figure 3.11 Scenario outputs for Test Scenario “Numbers recruited increase from zero whilst Habitat quality is medium and steady.

Controlling behaviour of Net Survival Dynamic derivative in simulations

Whilst the model fragments described above do generate the desired behaviour path (Table 3.2) there are still some undesirable behaviours and erroneous end-states. Interrogation of the behaviour paths and dependency diagrams indicate that these erroneous end states related to inconsistent behaviour relating to the derivative behaviour *Net survival dynamic* when both *Numbers recruited* and *Habitat quality* give a dynamic behaviour to *Population potential*. This relates to situations where changing *Population potential* gives rise to a change in *Numbers surviving* through the *Net survival dynamic* calculation and I+ [*Net survival dynamic*, *Numbers surviving*]. 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 work until 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). Therefore, three child model fragments were defined for each model fragment from Mf6a to Mf6l. These model fragments determine that when *Population potential* and *Numbers surviving* are either both increasing or both decreasing that the magnitude difference between them remains the same or decreases. This means that they are increasing or decreasing at rates which are either equal (Net survival dynamic has steady derivative) or causing the value of *Net survival dynamic* to move towards zero. This was achieved with three model fragments (Figure 3.12 gives the examples for the children of Mf6a, all other solutions are in Appendix 1):

1) Child (1) where Net survival dynamic is plus - the derivative of NSD is fixed depending upon the values of the Population potential. In situations where Habitat quality is unequal to Number recruited (Mf6a and Mf6b) then this is done by the means of a calculus subtraction between the derivatives of Number surviving and Population potential, the result of which determines the derivative of NSD and is restricted to steady or decreasing. Where Habitat quality is equal to Number recruited (Mf6d to Mf6l) then the derivative of NSD is fixed as a consequence.
2) Child (2) where Net survival dynamic is zero - the derivative of NSD is fixed using a directed derivative correspondence between Population potential and NSD.
3) Child (3) where Net survival dynamic is minus - the derivative of NSD is fixed depending upon the values of the Population potential. In situations where Habitat quality is unequal to Number recruited (Mf6a and Mf6b) then this is done by the means of a calculus subtraction between the derivatives of Number surviving and Population potential, the result of which determines the derivative of NSD and is restricted to steady or increasing. Where Habitat quality is equal to Number recruited (Mf6d to Mf6l) then the derivative of NSD is fixed as a consequence.

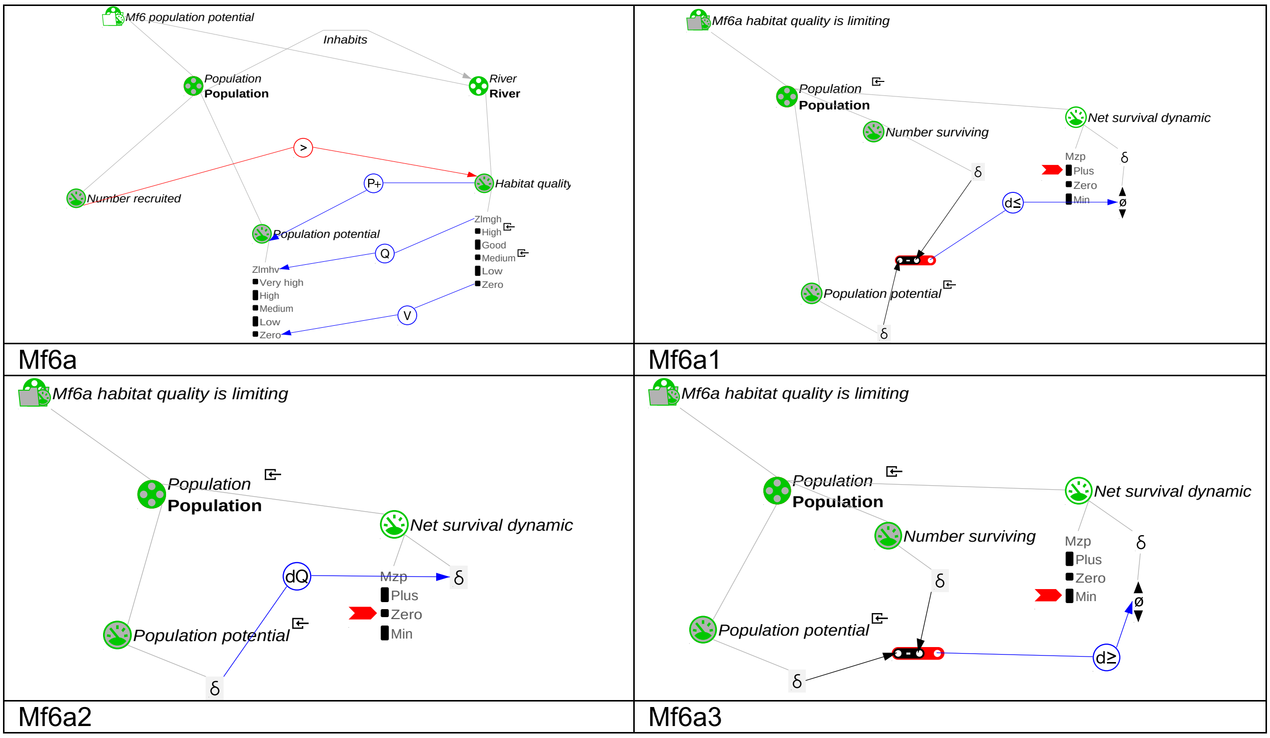


Figure 3.12 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6a (*Number recruited > Habitat quality*) determines the *Population potential*.

Test scenarios - simulations including model fragments controlling derivative behaviour of Net survival dynamic

Following the integration of the model fragments which control the derivative behaviour of Net survival dynamic all of the test scenarios for single life stages produced appropriate behaviour path ways with no erroneous end states. Examples of Test S1, Test S7 and Test S5 are shown here to indicate the expected behaviour of a single life stage in different scenarios for recruitment and habitat quality.

Table 3.3 Simulation of scenario "Test S1 - Habitat quality declines from High and Number recruited is Highly abundant and steady".

Scenario Name	Test S1 - *Habitat quality* declines from High and *Number recruited* is Highly abundant and steady
Full simulation	16 states
Initial States	[1]
End states	[16]
Relevant behaviour path	[1, 2, 3, 5, 7, 10, 15, 16] plus any path from [1] to [16]
Behaviour description	In this scenario the *Number recruited* and *Habitat quality* are controlled by exogenous behaviours. In state [1] *Number recruited* is Highly abundant and steady and *Habitat quality* is High but decreasing exogenously. Therefore in state [1] the *Population potential* is Very high and decreasing. In state [2] as *Habitat quality* has declined to Good, *Population potential* is now High and decreasing. This means that the potential is less than the *Number surviving* (High) so that *Net survival dynamic* is minus and therefore acts to reduce the *Number surviving* (I+ *Net survival dynamic*, *Number surviving*). From states [3] to [10] population continues to decline in response to declining habitat quality and the net survival dynamic acts to reduce the *Number surviving*. *Number surviving* reaches zero by state [16] when *Population potential* has reaches zero (in state [10]) and *Net survival dynamic* acts to make the *Numbers surviving* match the potential.

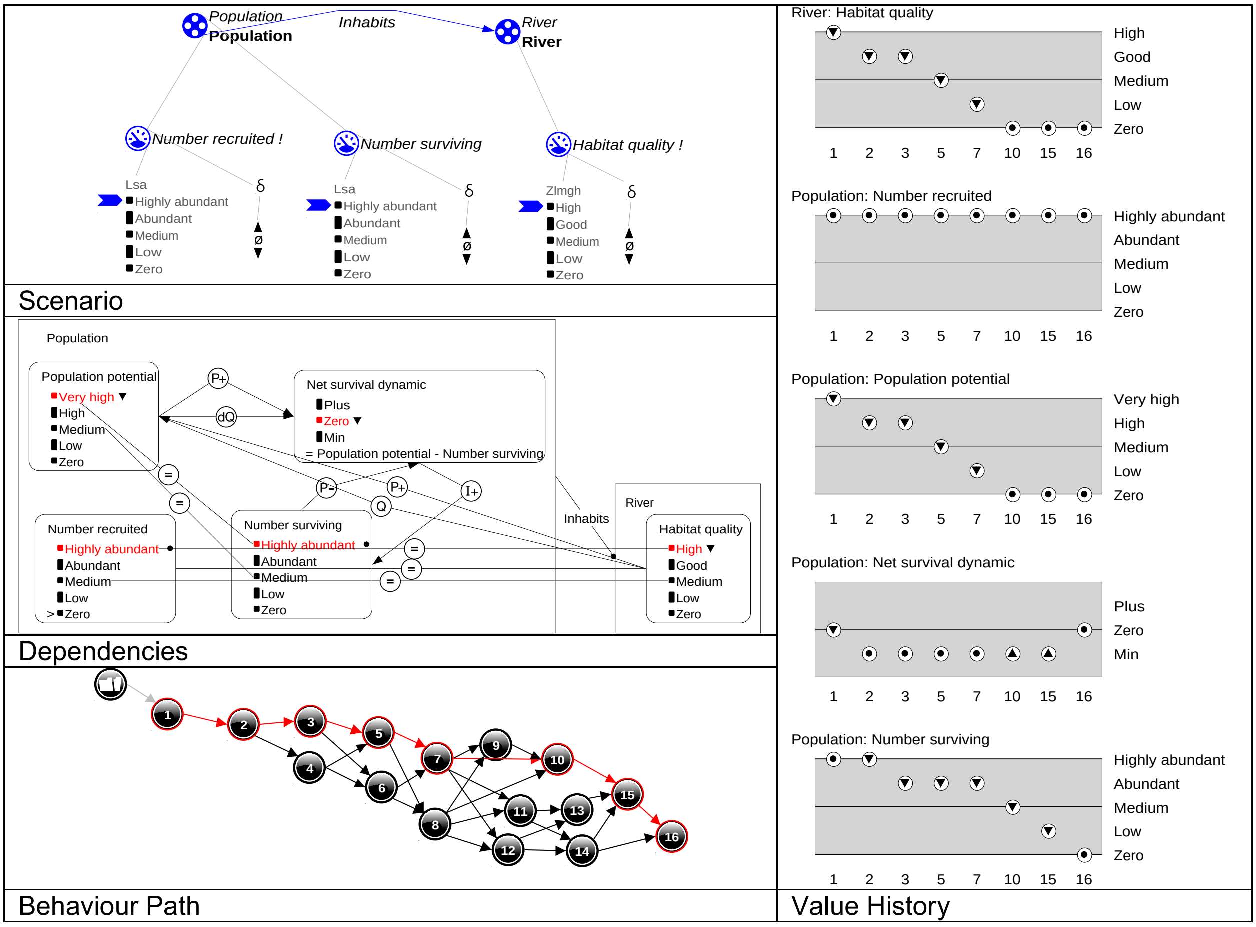


Figure 3.13 Simulation of scenario "Test S1 - Habitat quality declines from High and Number recruited is Highly abundant and steady".

Table 3.4 Simulation of scenario "Test S7 - Habitat quality is medium and steady whilst Number recruited increases from zero"

Scenario Name	Test S7 - Habitat quality is medium and steady whilst Number recruited increases from zero
Full simulation	10 states
Initial States	[1]
End states	[9]
Relevant behaviour path	[1, 2, 3, 5, 8, 9] or any path [1] to [9]
Behaviour description	In this scenario the *Number recruited* and *Habitat quality* are controlled by exogenous behaviours. In state [1] *Number recruited* is zero but increasing and *Habitat quality* is medium and steady. Therefore in state [1] the *Population potential* is zero and increasing as it is limited by recruitment. In state [2] as *Number recruited* has increased to low, *Population potential* is now low and increasing. This means that the potential is greater than the *Number surviving* (zero) so that *Net survival dynamic* is plus and therefore acts to increase the *Number surviving* (I+ *Net survival dynamic*, *Number surviving*). From states [2] to [5] population continues to increase in response to increasing recruitment and the net survival dynamic acts to increase the *Number surviving*. However, in state [5] Population potential is now medium and steady as it is now limited by the Habitat quality. *Number surviving* reaches medium by state [9] when *Net survival dynamic* has acted to make the *Numbers surviving* match the potential.

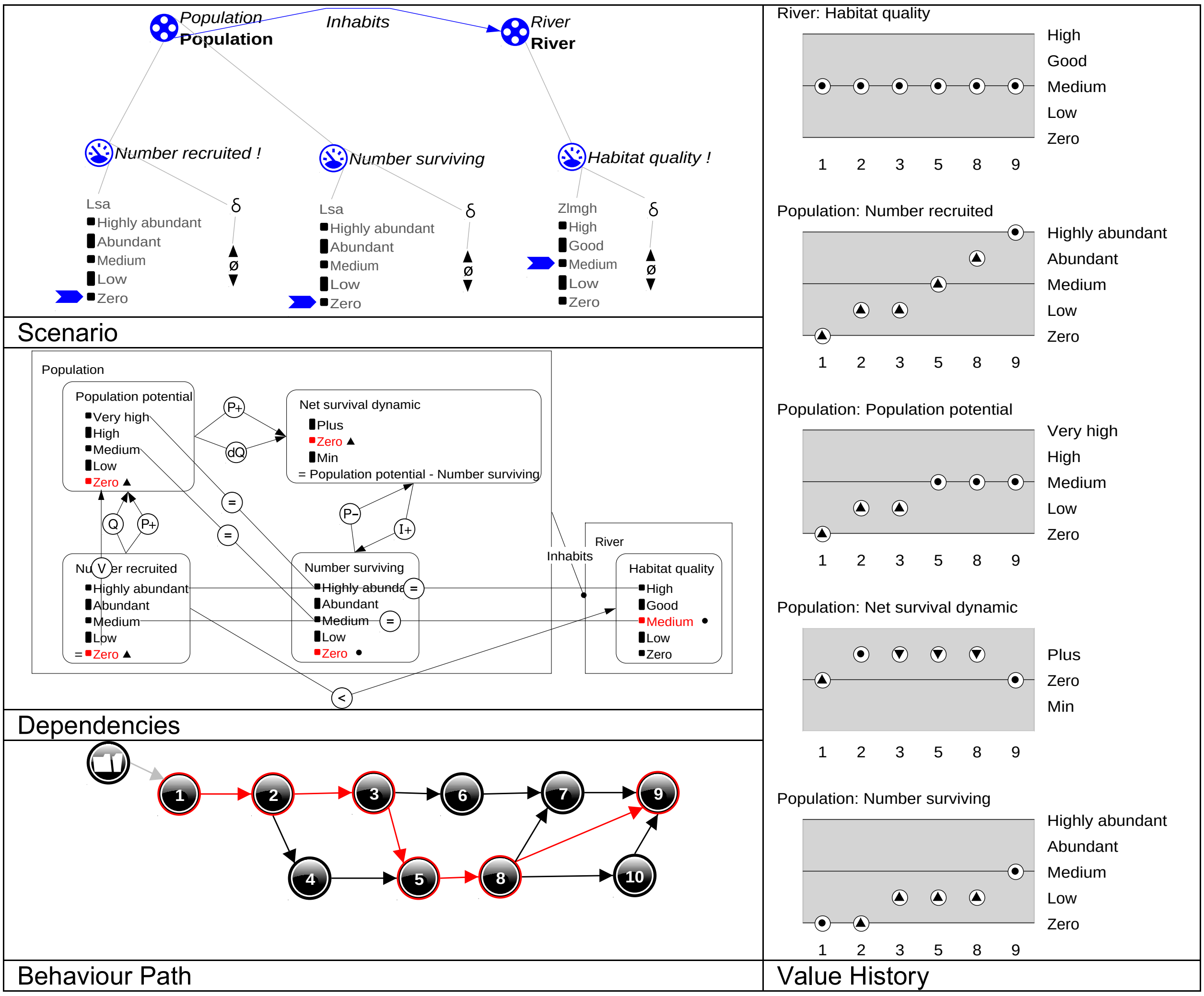


Figure 3.14 Simulation of scenario "Test S7 - Habitat quality is medium and steady whilst Number recruited increases from zero".

Table 3.5 Simulation of scenario “Test S5 - Habitat quality is decreasing from high and Number recruited increases from zero”

Scenario Name	Test S5 - Habitat quality is decreasing from high and Number recruited increases from zero
Full simulation	78 states
Initial States	[1]
End states	[50]
Relevant behaviour path	[1, 2, 3, 10, 11, 24, 26, 50] or any path [1] to [50]
Behaviour description	In this scenario the *Number recruited* and *Habitat quality* are controlled by exogenous behaviours. In state [1] *Number recruited* is zero but increasing and *Habitat quality* is high and decreasing. Therefore, in state [1] the *Population potential* is zero and increasing as it is limited by recruitment. In state [2] as *Number recruited* has increased to low, *Population potential* is now low and increasing. This means that the potential is greater than the *Number surviving* (zero) so that *Net survival dynamic* is plus and therefore acts to increase the *Number surviving* (I+ *Net survival dynamic*, *Number surviving*). From states [2] to [10] population continues to increase in response to increasing recruitment and the net survival dynamic acts to increase the *Number surviving*. However, in state [10] Population potential is now medium and steady as it is now limited by the Habitat quality. From state [11] to [50] Population potential declines matching the declining *Habitat quality*. In state [10] *Number surviving* reaches medium by when *Net survival dynamic* has acted to make the *Numbers surviving* match the *Population potential*. At this point *Net survival dynamic* has returned to zero. After state [11] *Population potential* becomes lower than the *Number surviving* and *Net survival dynamic* becomes minus acting to reduce the *Number surviving* until the become zero matching the potential in state [50].

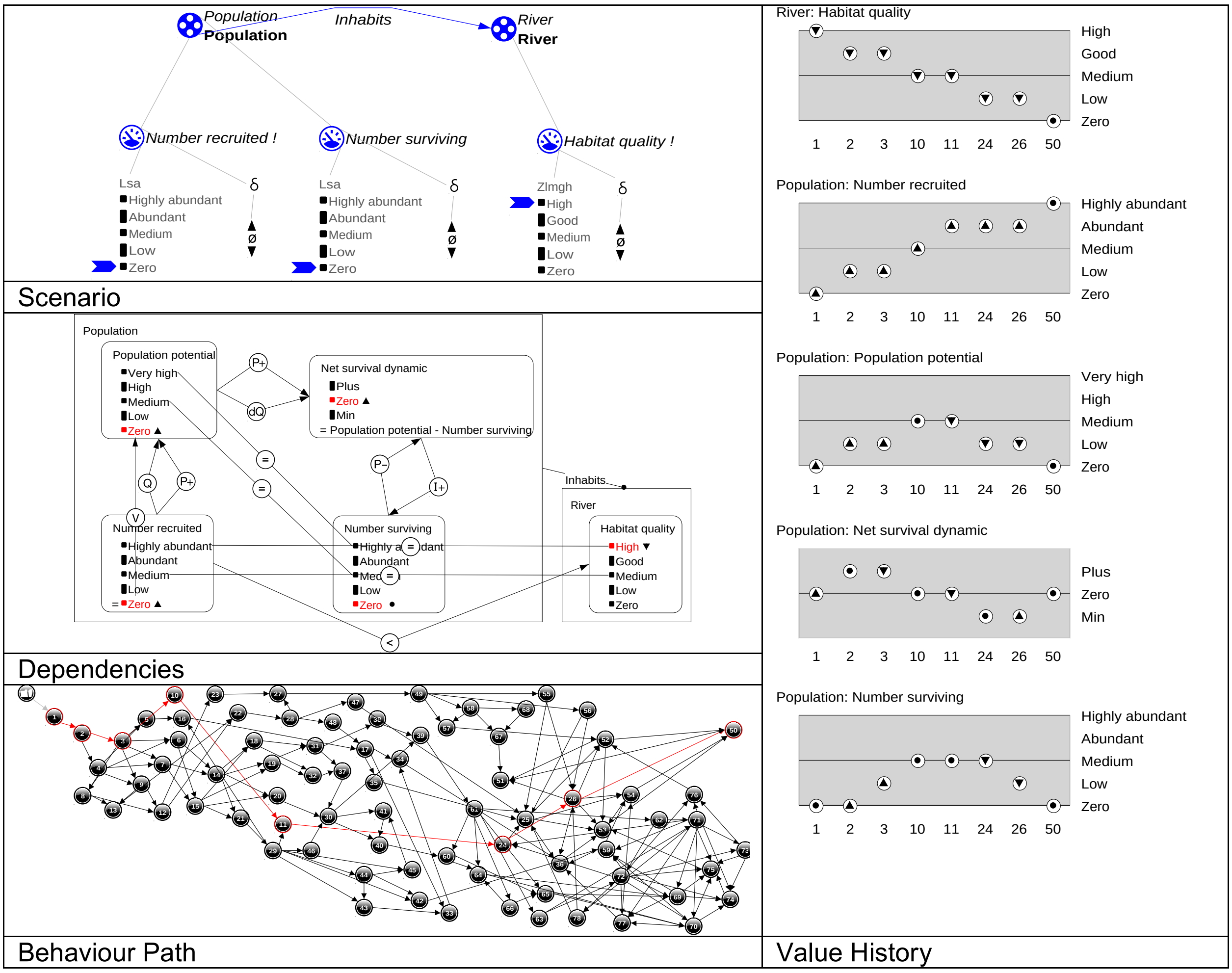


Figure 3.15 Simulation of scenario “Test S5 - Habitat quality is decreasing from high and Number recruited increases from zero”.

3.2.4 Life stages and recruitment

Initial concepts and modelling approach

The initial modelling approach considered for the process of recruitment was the use of mortality/survival rates and recruitment rates to control the number of individuals for each life stage (mortality and survival implementation is considered in section 3.2.3). However, once the modelling approach shifted to focussing on the survival within a life stage, and giving each life stage two quantities to represent the numbers entering a life stage and the numbers surviving the life stage, then recruitment could just be considered to be the instantaneous transition from one life stage to the next. This allowed recruitment to be modelled simply by making a link between the number surviving one life stage and the number recruited to the next life stage.

Final modelling implementation

The life cycle model concept used in this case study relates the Numbers surviving one life stage to the Numbers recruited to the next life stage. This concept is defined by model fragment Mf4 which states that if there is one population that *Recruits into* (conditional configuration) another population (both denoted by re-using model fragment Mf1 as a condition) then there is a proportionality P+ *Numbers surviving* [1st Population], *Numbers recruited* [2nd Population]. This proportionality holds true for recruitment between all life stages (Figure 3.16). However, given that the generic scenario described for the salmon model allows for two additional forms of recruitment; stocking (enhancing the recruitment of juveniles by adding farm reared juveniles to the wild population) and immigration (the straying of adults from a neighbouring population enhancing the numbers of adults returning to the river); specific instances of recruitment need to be defined. Therefore, four child fragments were defined to account for recruitment between specific life stages in the absence of immigration and stocking (modelled using separate fragments, section 3.2.5).

The specific instances of life stage transitions (e.g. adult to egg) were denoted by using the life stage entities as conditions for the specific recruitment fragments to be active. The specific life stages were linked to the relevant population with the *Consists of* configuration as a condition. Mf4a controls recruitment between egg and juvenile in the absence of stocking (denoted using the No stocking of young juveniles assumption label). Mf4b controls recruitment between juvenile and sub adult. Mf4c controls recruitment between sub adult and adult in the absence of immigration (denoted using the “No immigration” assumption label). Mf4d controls recruitment between adult and egg (spawning). In all of these cases there is a full correspondence between the Number surviving of the younger life stage and the Number recruited to the subsequent life stage.

In the model the quantity spaces of Numbers recruited and Numbers surviving are qualitatively equal in as much as a medium number recruited can result (after the influence of survival/mortality within a life stage) in a medium number surviving. Quantitatively, however, the medium number surviving should be considered to be much less than the actual numbers recruited. In the consideration of Number surviving and number recruited between life stage transitions these values are considered both qualitatively and quantitatively equal for all life stage transitions other than between *Adult* and *Egg*. For most life stages the point of recruitment i.e. the maturation from one life stage to the next is modelled as an instantaneous event so that quantitatively a “medium” number surviving is exactly the same as “medium” recruited to the next life stage. For the transition from adult to egg life stages this recruitment represents spawning and as such the relationship between numbers of adults surviving and the numbers of eggs recruited is not considered as a fully quantitative relationship. In this recruitment transition the numbers of adults surviving is equated to a value of population fecundity (total number of eggs laid by a population of adults). Given than one female adult can produce 1000s of eggs, then whilst a “medium” number of adults produce a “medium” number of eggs, a medium number of eggs is quantitatively far higher than a medium number of adults.

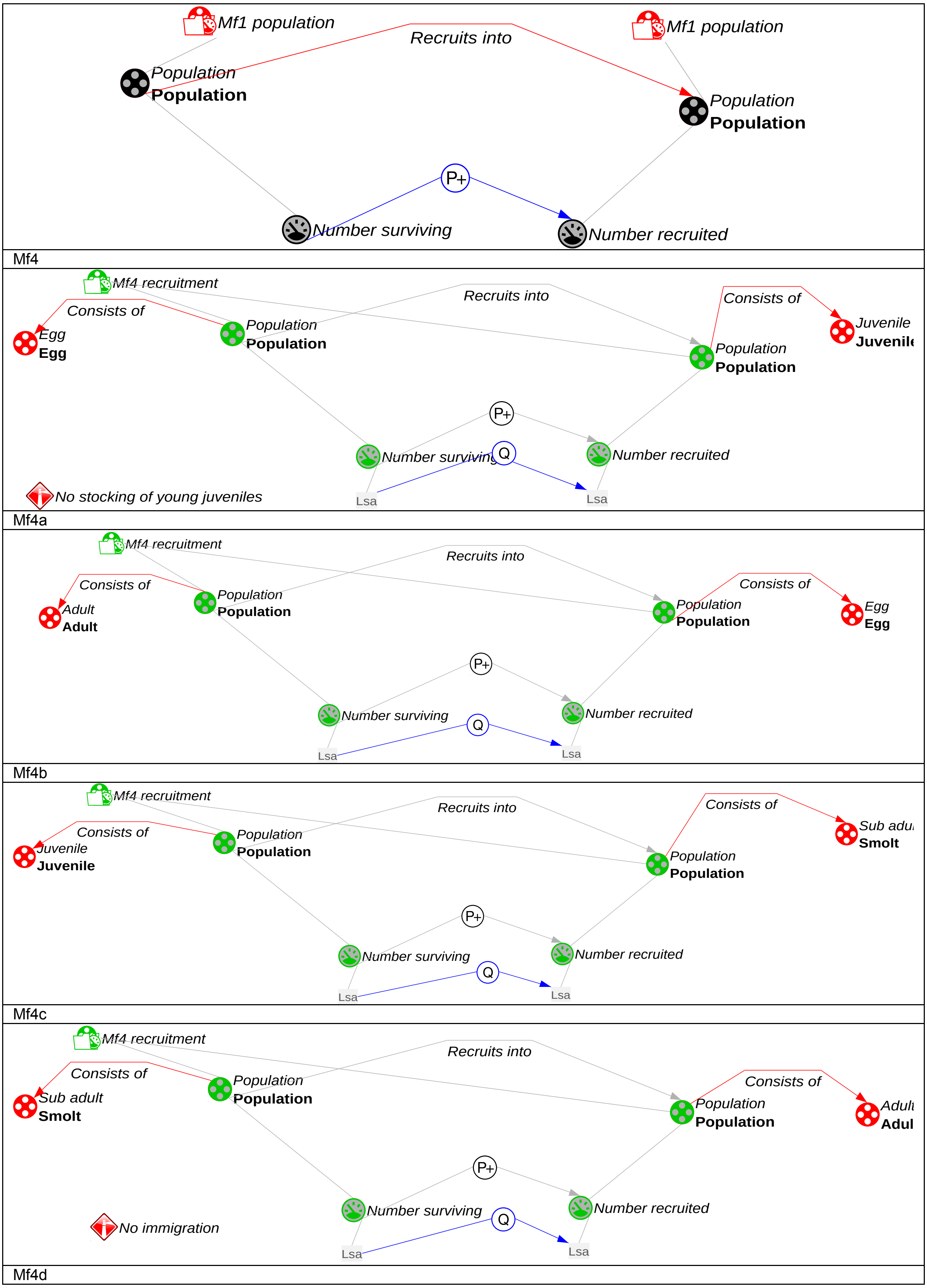


Figure 3.16 Model fragment Mf4 and children Mf4a-d denoting the process of recruitment between life stages.

3.2.5 Stocking and Immigration

Stocking and immigration are two specific instances where the population size of a species or life stage can be increased from outside of the population – effectively enhancing the levels of recruitment within the local population (Figure 3.17). Immigration from neighbouring populations is modelled in model fragment Mf a11, and is only considered for the salmon model. The immigration fragment will only be active if the assumption labels "Salmon model" and "Immigration active" are specified in a scenario. Additionally a neighbouring population that *is close to* the adult population must be specified in the scenario. If this is the case then Mf a11 supersedes Mf4d and controls the recruitment of smolts to adults. Essentially the *Straying rate* of the neighbouring population acts to top up the numbers of adults recruited so that is there are zero smolts surviving the numbers of adults recruited is low rather than zero. This is achieved using value correspondences from the values of Number surviving [*Smolt*] to Number recruited [*Adult*], fixing the values numbers recruited take for any value of number surviving. There is also a proportionality P+ *Number recruited*, *Straying rate* to indicate that if the straying rate increased or decreased that the number recruited would increase or decrease respectively. However, given that straying rate has a Zp quantity space then this value will usually remain fixed in a scenario.

Model fragment Mf a2 is an agent fragment which models the activity of a *Fishery manager* who *Stocks* the juvenile population. This is modelled using the same approach as immigration where the model fragment will only be active if the assumption "Stocking active" is specified in the scenario and a fishery manager agent is also specified as stocking the juvenile population. Stocking rate also only acts to top up the numbers recruited when the numbers of eggs surviving is less than abundant.

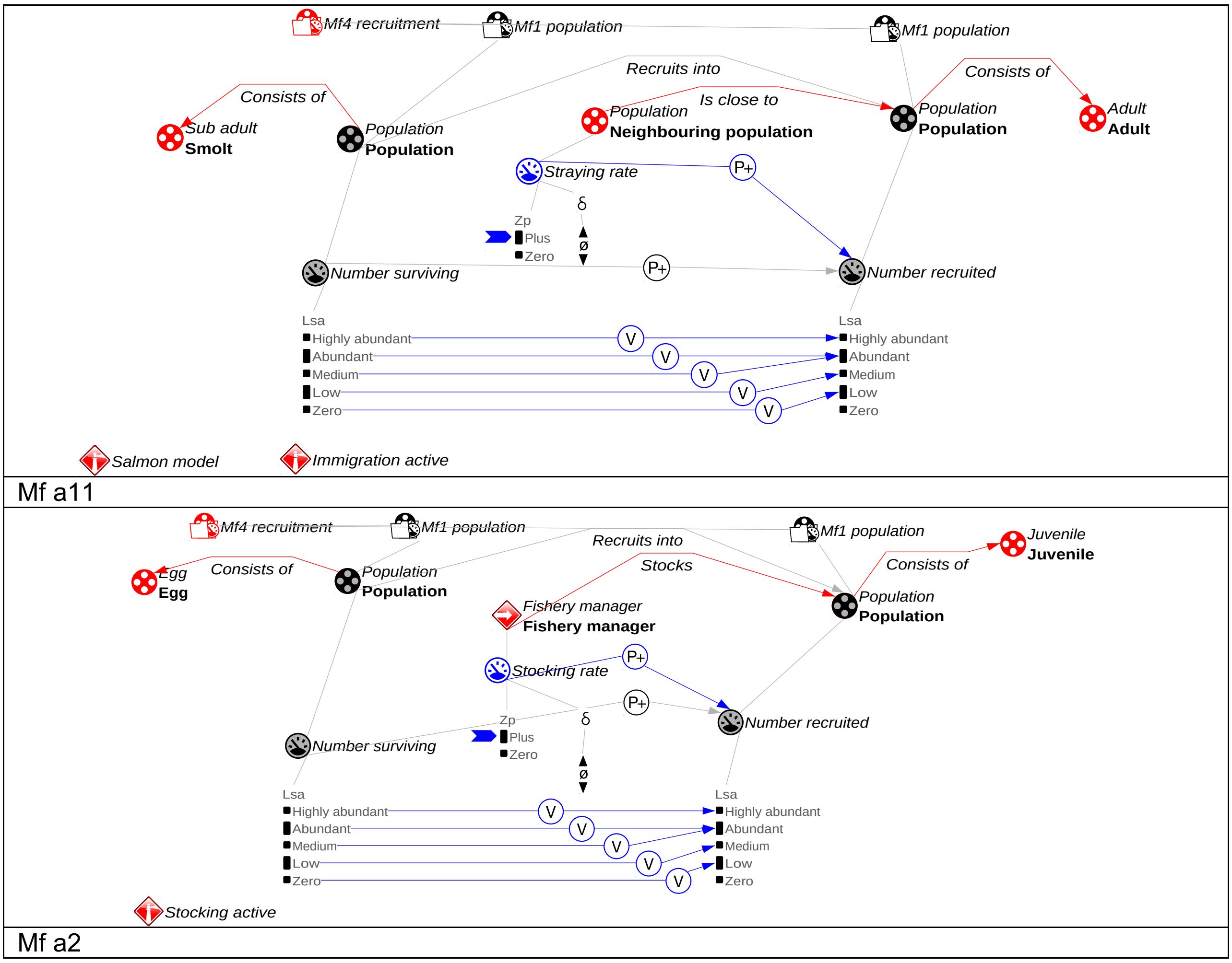


Figure 3.17 model fragments for the situations where immigration is active (Mf a11) or stocking is active (Mf a2).

This approach to modelling immigration and stocking is basic as it is fairly limited and the stocking and immigration rates must remain fixed. For the model to allow for both Numbers surviving and Stocking (or immigration) rate to be variable, and for both to vary together during a simulation, an alternative modelling approach would be required. This would probably comprise of some form of addition calculus.

3.2.6 External Human Influences – Agents, Degradation and Rehabilitation

Human activity within the UK case study is represented as agents that are active within the *Catchment* or active on the *River*. These are represented as either *Degradation agents* or *Rehabilitation agents*. Degradation agents represent human activities that utilise a river or its catchment to provide services to specific stakeholders and to the general human population. Rehabilitation agents represent groups that act to conserve and improve the environment, mitigating the effects that human activities can have.

Degradation Agents

Degradation agents are modelled using the same approach (Figure 3.18). All the degradation model fragments comprise the condition that a *Degradation agent* - *Occurs in* - a *Catchment*. If those conditions occur then the quantity *Intensity* is given to the *Degradation agent* and quantity is given to the *Catchment* reflecting some characteristic of the *Catchment* that relates to *Habitat quality* (see Figure 3.19). The quantity *Intensity* indicates how much of that human activity occurs within the catchment. For all degradation agents there is then a proportionality relation P+ “catchment characteristic”, *Intensity*. Additionally there is a full directed quantity space correspondence from the *Intensity* of the degradation agent to the characteristic of the catchment. The actions of all degradation agents considered in the model are summarised in table 3.6.

Table 3.6 Summary of degradation agents and their activity

Agent	Mf	Catchment/Habitat	Quantity	Comment
Agriculture	Mf a1	Upland	Sedimentation level	Agriculture in an upland catchment can act to increase the level of fine sediment run off into the upland river which can impact on the quality of salmon spawning gravels.
Agriculture	Mf a13	Floodplain	Extent of land drainage	Agriculture in a lowland catchment requires wetland to be drained to create arable land for crops.
Water industry	Mf a3	Upland	Water abstracted	The water industry abstracts water from the river for consumption and irrigation. Reduced water flows can reduce habitat quality and quality though reduced wetted area, reduced oxygenation, increased water temperature and reduced dilution of pollution.
River engineer	Mf a8	Lowland	Level of river engineering	River engineering in a lowland catchment due to channelisation and impoundment damages the general habitat quality and diversity and disrupts the connectivity of the river.

Rehabilitation agents

In the scenarios the impacts of a degradation agent can be countered by the rehabilitation activities of an *Environmental manager*. Thus habitat quality is dependent on the *Intensity* of activity of the degradation agent and the *Extent of rehabilitation* undertaken by the *Environmental manager* (see later paragraphs). All environmental manager model fragments are built using the same approach in that the *Environmental manager – rehabilitates –* a *River* or *Habitat* as a condition for the fragments being active. If the conditions are met in a scenario then the quantity *Extent of rehabilitation* is given to the *Environmental manager* and a quantity for a specific habitat quality or habitat feature is assigned to the *River* or *Habitat* (Figure 3.18). There is then also a proportionality relation P+ (Extent of rehabilitation, quality of habitat feature). This denotes that the habitat quality increases as the extent of rehabilitation occurs. The specific environmental manager fragments are described in Table 3.7.

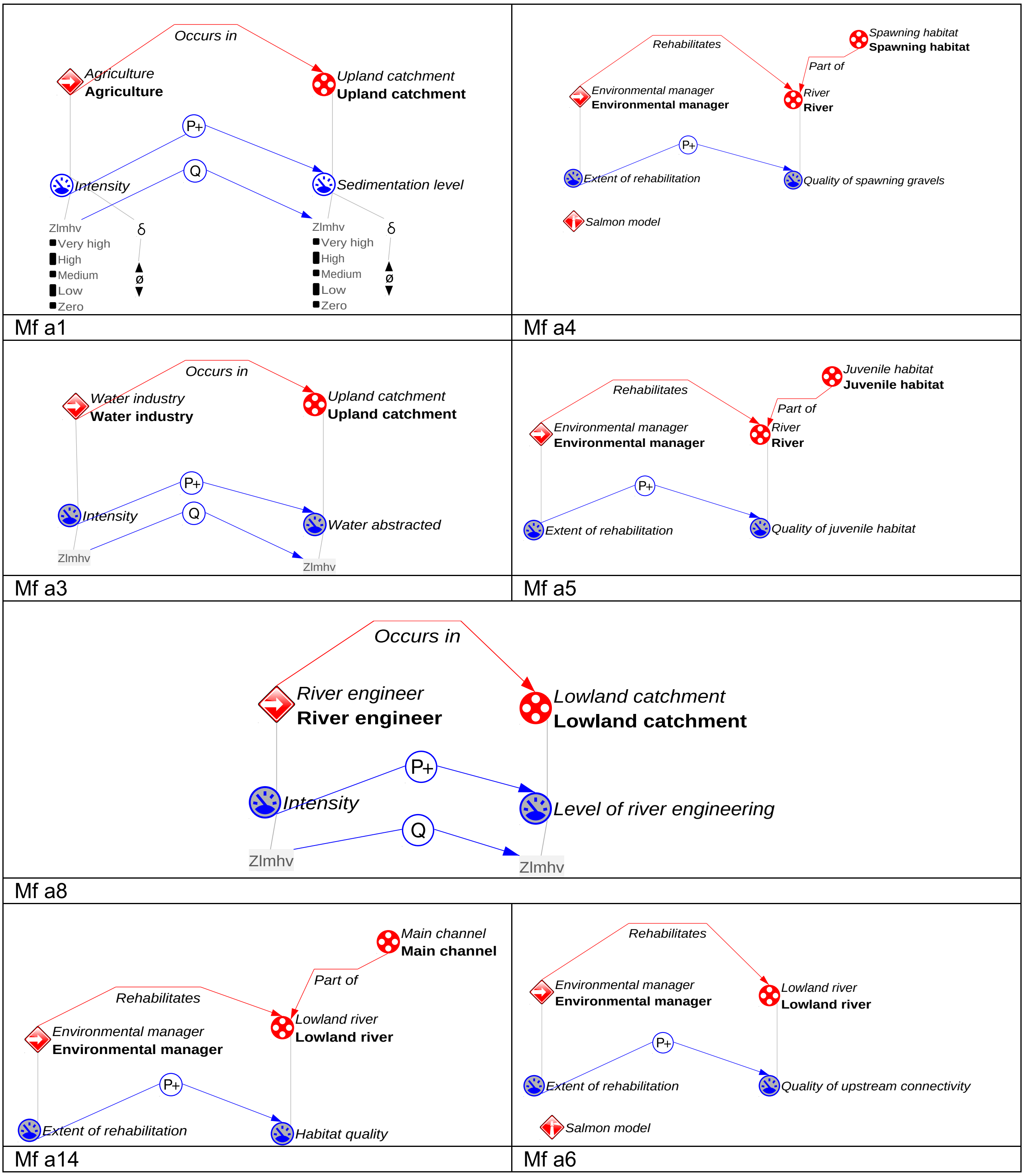


Figure 3.18 Agent model fragments used to represent the effects of humans on the river system and its catchment.

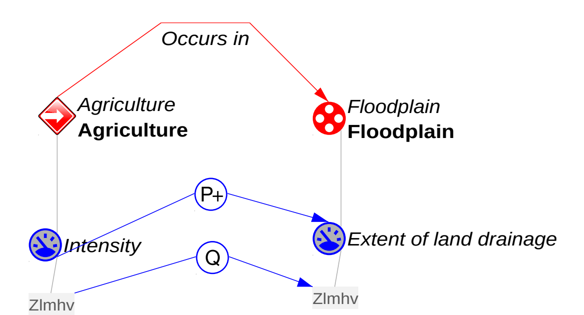
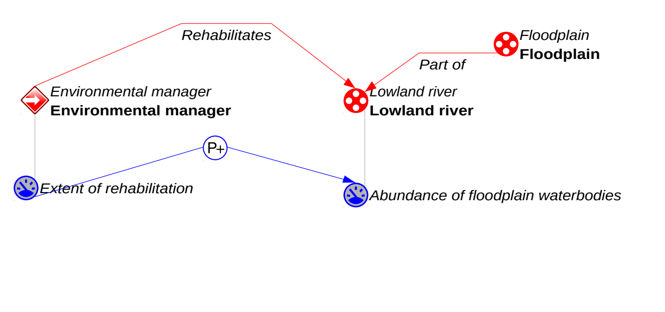
	
Mf a13	Mf a12

Figure 3.19 continued Agent model fragments used to represent the effects of humans on the river system and its catchment.

Table 3.7 Summary of model fragments for the activity of environmental managers in specific rivers and habitats.

Mf	River/Habitat	Quantity	Comment
Mf a4	River Spawning habitat	Quality of spawning gravels	The actions of an environmental manager cleaning the spawning gravels (reducing the amount of fine sediment) improve the quality of the spawning gravels. Only relevant for the salmon model so limited by the "Salmon model" assumption label.
Mf a5	River Juvenile habitat	Quality of juvenile habitat	This can apply for any rehabilitation activity that acts to improve habitat for juveniles – used in both the salmon and bream models.
Mf a6	Lowland river	Quality of upstream connectivity	The improvement of connectivity for migratory salmonids though creation of fish passes or removal of barriers. This only applies in the salmon model so is limited by the "salmon model" assumption label.
Mf a12	Floodplain	Abundance of floodplain waterbodies	Creation of new floodplain waterbodies (e.g. creation of gravel pits) or the reconnection of existing water bodies to the main river channel.
Mf a14	Lowland river Main channel	Habitat quality	Rehabilitation of the main channel of a lowland river to improve habitat quality and diversity mitigating the effects of river engineering.

The actions of degradation agents and their effects on the catchment characteristics are related to the quality of specific habitats in six model fragments (Figure 3.20). Two model fragments deal with spawning habitats (Mf10) and juvenile habitats (Mf12) in upland river catchments (children of Mf8). Four model fragments deal with habitats in the lowland catchment (children of Mf9); salmonid migration (Mf14), juvenile habitat (Mf20), floodplain habitat (Mf22) and main channel habitat (Mf24). All of these fragments relate the catchment or river characteristic (e.g. *Sedimentation level*) to the quality of a habitat using a proportionality relation P- (catchment characteristic, habitat quality) (e.g. P-(*Sedimentation level*, *Quality of spawning gravels*).

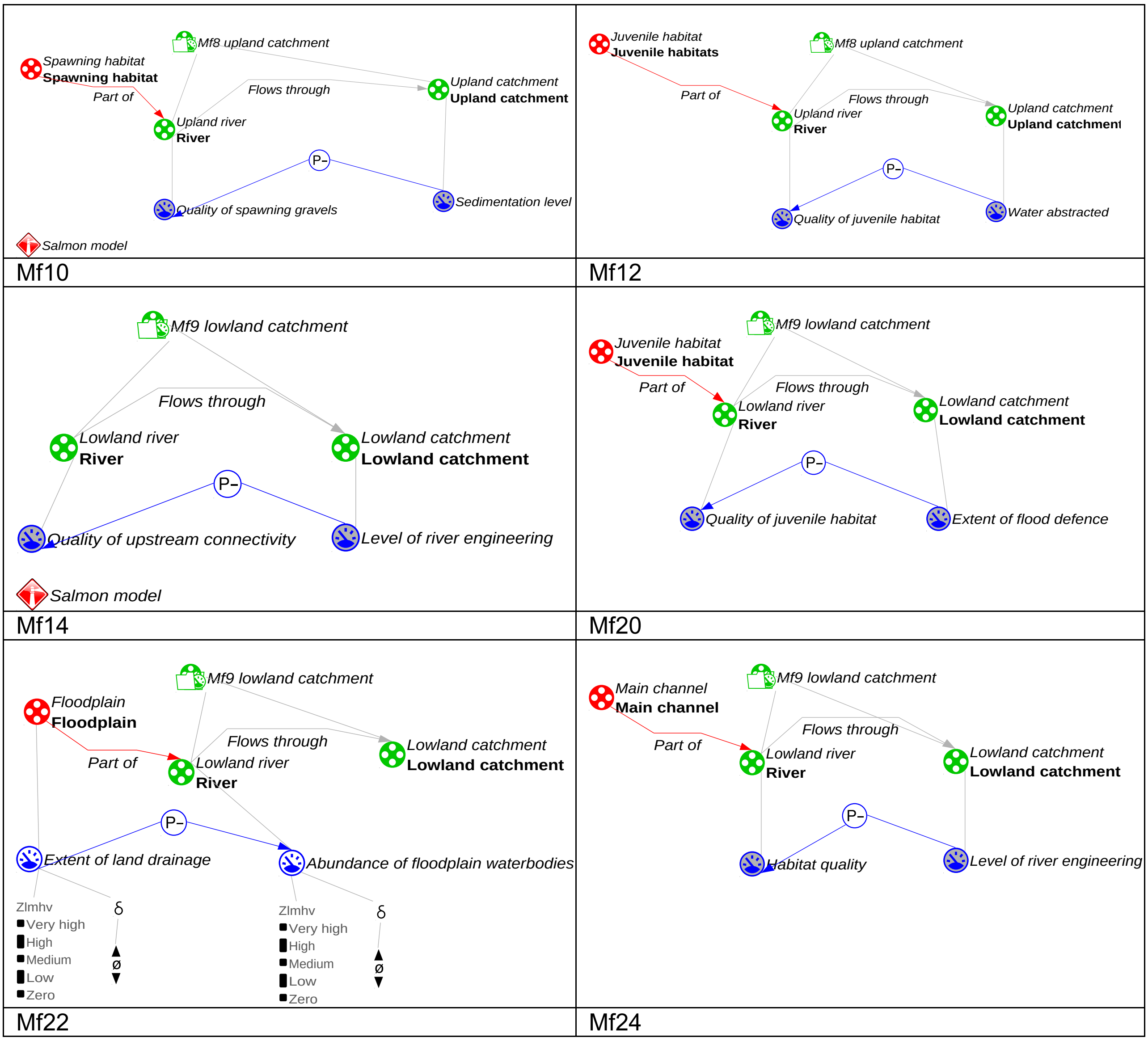


Figure 3.20 Model fragments used to relate characteristics of a *Catchment* to the *Habitat quality* for specific *River*s and *Habitat*.

Derivation of Habitat quality at different levels of human activity and rehabilitation

The combined effect of habitat degradation though human activities and rehabilitation on the habitat quality of a river or environment is modelled using a suite of fragments for specific pairs of degradation activity and rehabilitation activity in a specific habitat/river type. In this section a full description is given of model fragments for the derivation of upland river salmonid spawning habitat. These fragments balance the effects of the level of sedimentation in the upland catchment (Mf a1 and Mf10) and cleaning of spawning gravels by an environmental manager (Mf a4) on the *Quality of spawning habitat*. The modelling approach used for each of the degradation/rehabilitation pairs is very similar so only a summary of the model fragments and combinations is given for the other pairs (Table 3.8).

The modelling approach used for all combinations of degradation activity/rehabilitation activity and habitat type uses the concept that the habitat quality is primarily determined by the catchment characteristic affected by the degradation agent and that the extent of rehabilitation can act to make conditions better. The level to which rehabilitation can improve the habitat quality varies depending on the initial level of impact of the degradation agent. Therefore, six model fragments were built for each degradation/rehabilitation pair, one of which is a parent fragment linking together the specific degradation and rehabilitation activities. Five child fragments are then described for each pair where the value of the catchment characteristic affected by the degradation activity is used as a conditional statement and then consequential directed value correspondences are then modelled between the values for the *Extent of rehabilitation* and the habitat quality under consideration. This equates to using a table of allowable values for habitat quality depending on the extent of the degradation and the extent of rehabilitation. A generic example of this is shown in Table 3.8.

Table 3.8 Matrix of allowable values for the quality of a habitat (Consequence) based on the combined values of degradation intensity (Conditional) and the rehabilitation that is applied.

Habitat quality Matrix		**Extent of rehabilitation**				
		Zero	Low	Medium	High	Very High
Degradation	Very High	*Zero*	*Low*	*Medium*	*Good*	*Good*
	High	*Low*	*Medium*	*Good*	*Good*	*Good*
	Medium	*Medium*	*Good*	*Good*	*Good*	*High*
	Low	*Good*	*Good*	*High*	*High*	*High*
	Zero	*High*	*High*	*High*	*High*	*High*

Model fragment Mf11 acts as the parent fragment for determination of the quality of spawning gravels. The fragment itself is a child of model fragment Mf10. In model fragment Mf11 the fragment “Mf a4 gravel cleaning” is added as a condition for Mf11 to be active. Identity relations are made between the *Spawning habitat* and *River* entities specified in both Mf10 and Mf a4 to indicate that both fragments are considering the same *Spawning habitat* and that the *River* in Mf a4 is the same as the *Upland river* in Mf10. This fragment then acts as the parent fragment for model fragments Mf11a to Mf11e which specify the habitat quality under specific conditions (Figures 3.21 and 3.22). These five child fragments implement the table of allowable values (Table 3.9) for the combination of *Sedimentation level* and *Extent of rehabilitation* which control the effects of rehabilitation and the resulting habitat quality for spawning habitats.

Table 3.9 Matrix of allowable values for the *Quality of spawning habitat* based on the combined values of *Sedimentation level* and the *Extent of rehabilitation* that is applied.

Spawning habitat quality Matrix		**Extent of rehabilitation**				
		Zero	Low	Medium	High	Very High
Sedimentation level	Very High (Mf11b)	*Zero*	*Low*	*Medium*	*Good*	*Good*
	High (Mf11c)	*Low*	*Medium*	*Good*	*Good*	*Good*
	Medium (Mf11d)	*Medium*	*Good*	*Good*	*Good*	*High*
	Low (Mf11e)	*Good*	*Good*	*High*	*High*	*High*
	Zero (Mf11a)	*High*	*High*	*High*	*High*	*High*

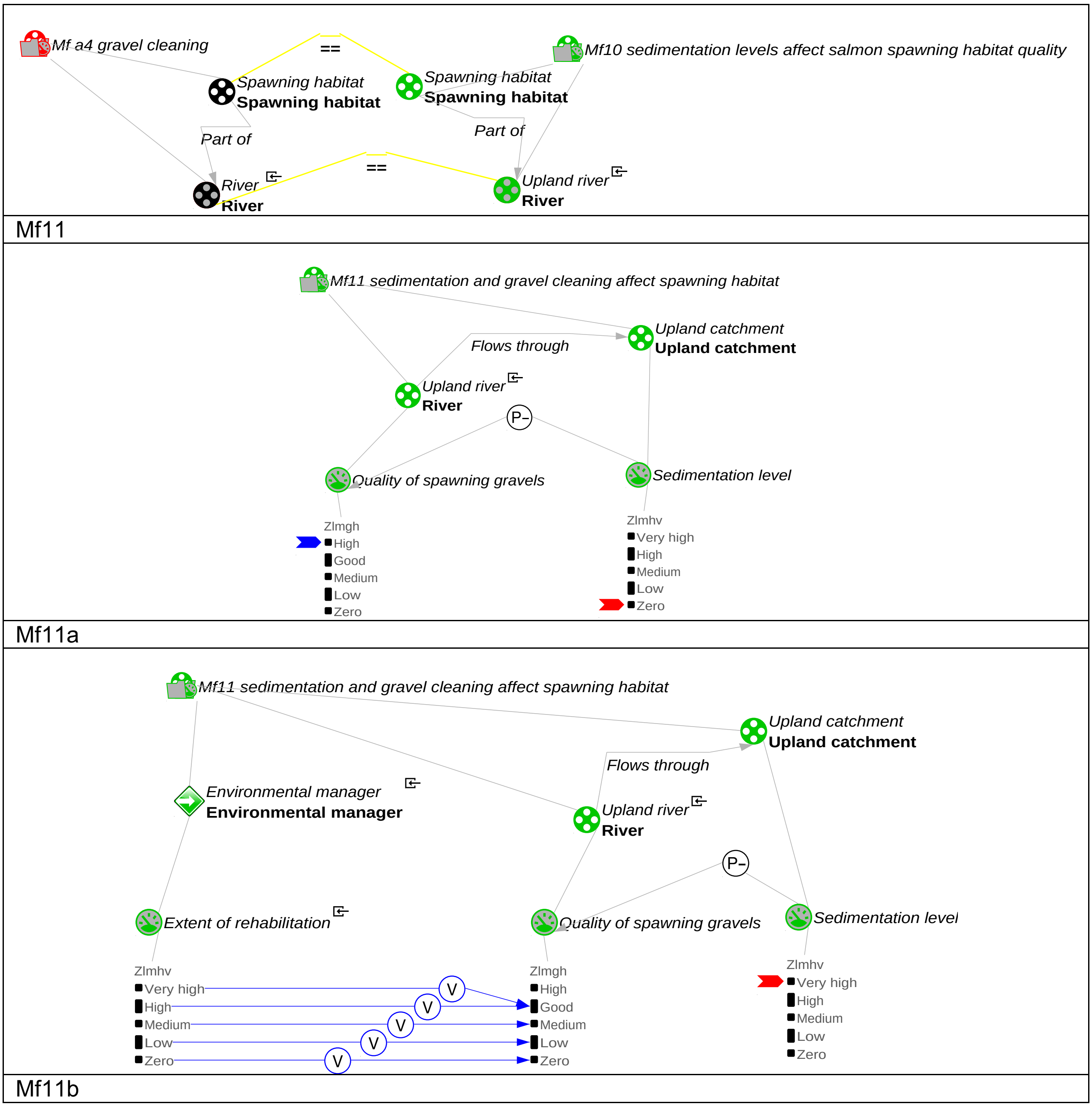


Figure 3.21 The suite of model fragments used to generate the value for the quality of spawning gravels in spawning habitat for the salmon model. The value of the *Quantity of spawning gravels* depends on the balance between the *Sedimentation level* and the *Extent of rehabilitation*.

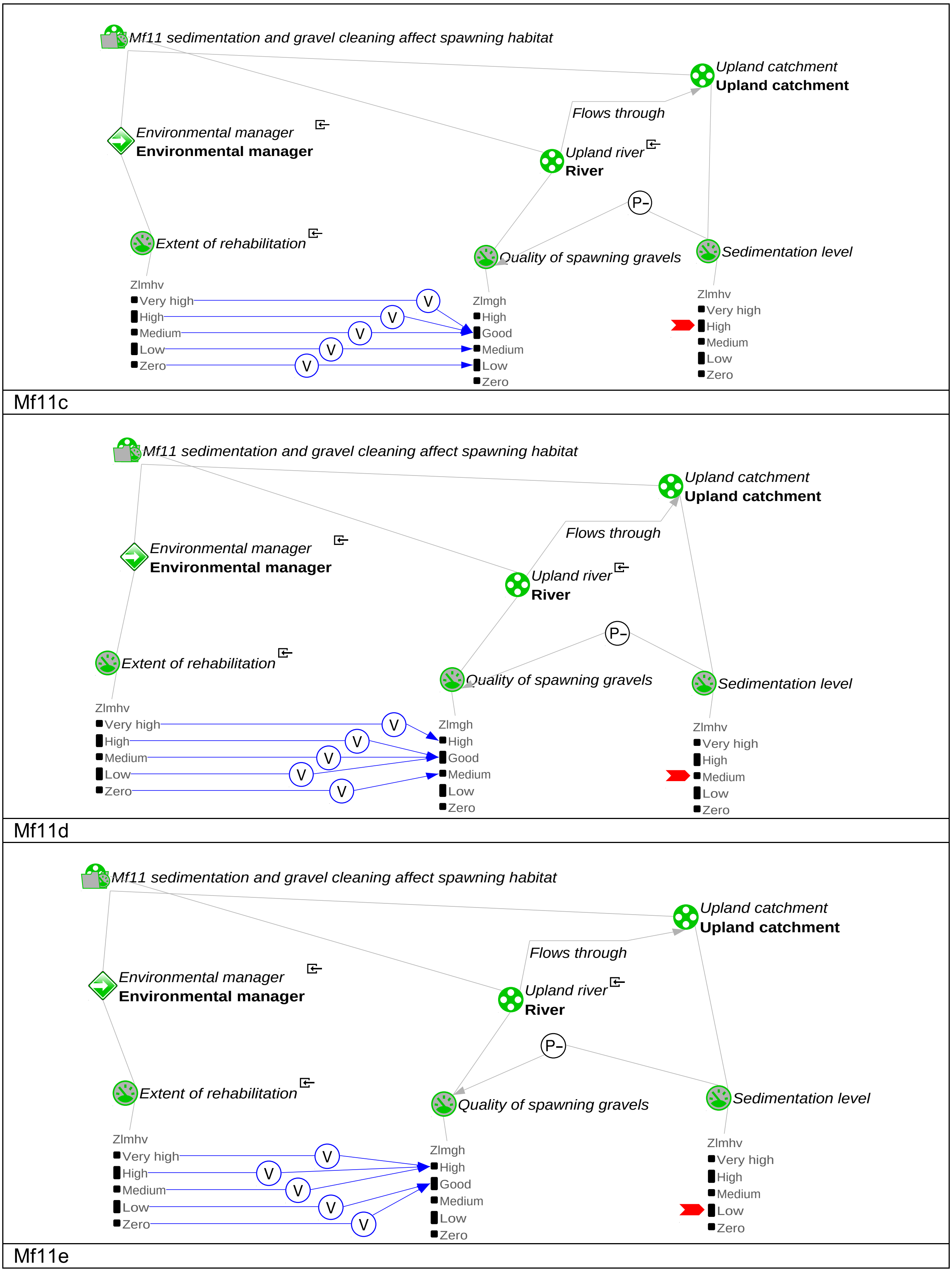


Figure 3.22 The suite of model fragments used to generate the value for the quality of spawning gravels in spawning habitat for the salmon model. The value of the *Quantity of spawning gravels* depends on the balance between the *Sedimentation level* and the *Extent of rehabilitation*.

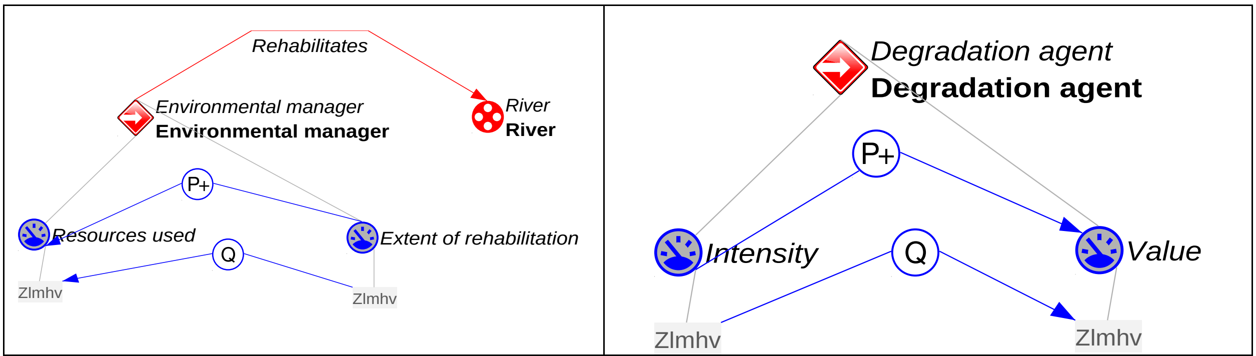
Table 3.10 summary of the model fragments used to derive habitat quality for a river/habitat under the influence of a pair of degradation/rehabilitation activities.

Concept	
Sedimentation affects the quality of salmon spawning gravels – Spawning gravels can be cleaned by an environmental manager	
Model fragments involved	Comment
Mf3a, Mf8, Mf10, Mf11 (plus children 11a to 11e), Mf a1, Mf a4	Described in main text Used in the River Trent salmon model
Abstraction influences water flows which relate to the quality of juvenile salmon habitats – juvenile habitats can be rehabilitated by an environmental manager	
Model fragments involved	Comment
Mf3c, Mf8, Mf12, Mf13 (plus children 13a to 13e), Mf a3, Mf a5	The quantities *Water abstracted* and *Extent of rehabilitation* are used to set values for *Quality of juvenile habitat* of an *Upland river*. Used in the River Trent salmon model
River engineering affects the connectivity of lowland rivers for migrating salmon – environmental managers can improve connectivity by construction of fish passes or removal of redundant barriers	
Model fragments involved	Comment
Mf3e, Mf9, Mf14, Mf15 (plus children 15a to 15e), Mf a6, Mf a8	The quantities *Extent of river engineering* and *Extent of rehabilitation* are used to set values for *Quality of upstream connectivity*. This suite of fragments only applies to salmon migrating through a lowland river. Used in the River Trent salmon model
River channel engineering affects the general habitat quality of lowland river channels - habitats can be rehabilitated by an environmental manager	
Model fragments involved	Comment
Mf9, Mf24, Mf25 (plus children 25a to 25e) Mf a14, Mf a8	The quantities *Extent of river engineering* and *Extent of rehabilitation* are used to set values for *Habitat quality*. Used in the Great Ouse bream model
Land drainage reduces the availability of floodplain waterbodies – floodplain habitats can be recreated/rehabilitated by an environmental manager	
Model fragments involved	Comment
Mf3d, Mf9, Mf23 (plus children 23a to 23e), Mf a12, Mf a13	The quantities *Extent of land drainage* and *Extent of rehabilitation* are used to set values for *Amount of floodplain waterbodies*. Used in the Great Ouse bream model
Flood defence measures reduce the quality and quantity of potential marginal habitats used by juveniles in lowland rivers – marginal habitats can be rehabilitated by an environmental manager	
Model fragments involved	Comment
Mf9, Mf20, Mf21 (plus children 21a to 21e), Mf a5	The quantities *Extent of flood defence* and *Extent of rehabilitation* are used to set values for *Quality of juvenile habitat* in a lowland river. Used in the Great Ouse bream model

Value of human activity and cost of rehabilitation

The UK case studies aimed to integrate elements of the social and economic aspects of sustainable development and river management. The final model integrates two aspects; the value generated to stakeholders and the general population and the cost of rehabilitation. Model fragment Mf a7 describes that as rehabilitation is undertaken resources are used. The *Resources used* by an *Environmental manager* can be economic, human or technical resources. This is modelled so that there is a proportionality relation P+ (*Resources used*, *Extent of rehabilitation*) and a directed correspondence describing that the more rehabilitation that is done the more resources used and the higher the cost (Figure 3.23).

Model fragment Mf a9 describes that the actions of a degradation agent (representing a human activity) are of *Value* to the human population. This value can be considered to be both economic and social e.g. Agriculture generates economic value and social well being though production of essential goods. The *Value* is modelled to be proportional to the *Intensity* of the activity, P+ (*Value*, *Intensity*). There is also a directed correspondence from *Intensity* to *Value* (Figure 3.23). This models a basic behaviour that the value of an activity is directly related to the intensity of its activity.



Mf a7	Mf a9

Figure 3.23 Model fragments Mf a7 and Mf a9 describing the value generated by the activity of a degradation agent and the resources used by an environmental manager undertaking rehabilitation.

Scenario – Test S10 Rehabilitation of a spawning habitat

The effects of sedimentation and rehabilitation on the quality of spawning habitat can be examined in a simple scenario of the *Spawning habitat* of an *Upland river* in an *Upland catchment* with an *Environmental manager* that rehabilitates the river (Figure 3.24). In the scenario exogenous behaviours are used to control the *Sedimentation level* (Very high and steady) and the *Extent of rehabilitation* (Zero and increasing). This scenario applies to the River Trent salmon model so the assumption label “Salmon model” is included in the scenario.

The output of this scenario summarised in table 3.10. Such a scenario can be generated for each of the degradation/rehabilitation combinations and for different starting levels of Intensity of degradation. This type of scenario can be integrated into the full life cycle scenario to look at the effect of rehabilitation of habitats on the dynamics of a fish population.

Table 3.10 Summary of behaviour for a scenario where the extent of rehabilitation (gravel cleaning) increases from zero whilst sedimentation level is very high and steady”.

Scenario Name	Test S10 Rehabilitation of a spawning habitat
Full simulation	5 states
Initial States	[1]
End states	[5]
Relevant behaviour path	[1, 2, 3, 4, 5]
Behaviour description	In state [1] The sedimentation level is high and the extent of rehabilitation is zero (increasing due to exogenous behaviour), therefore the Quality of spawning gravels is zero but increasing (due to the proportionality with the increasing rehabilitation). As the extent of rehabilitation increases the quality of spawning gravels increases (states [2, 3 & 4]). In the final state [5] the extent of rehabilitation is high but the quality of spawning gravels is only good, indicating the concept that even with intensive rehabilitation that the quality of spawning habitats cannot be high when the sedimentation level is very high. As rehabilitation is undertaken the resources used increase to Very high in state [5].

The modelling approach used here allows the generation of scenarios where the effects of changes in the level of rehabilitation on the quality of habitat can be examined for a set level of human activity. The modelling approach used does not easily allow both rehabilitation and degradation activities to have dynamic behaviours to their extent or intensity, respectively. A more complicated modelling approach would allow both the extent of rehabilitation and the intensity of a human activity to have dynamic behaviours.

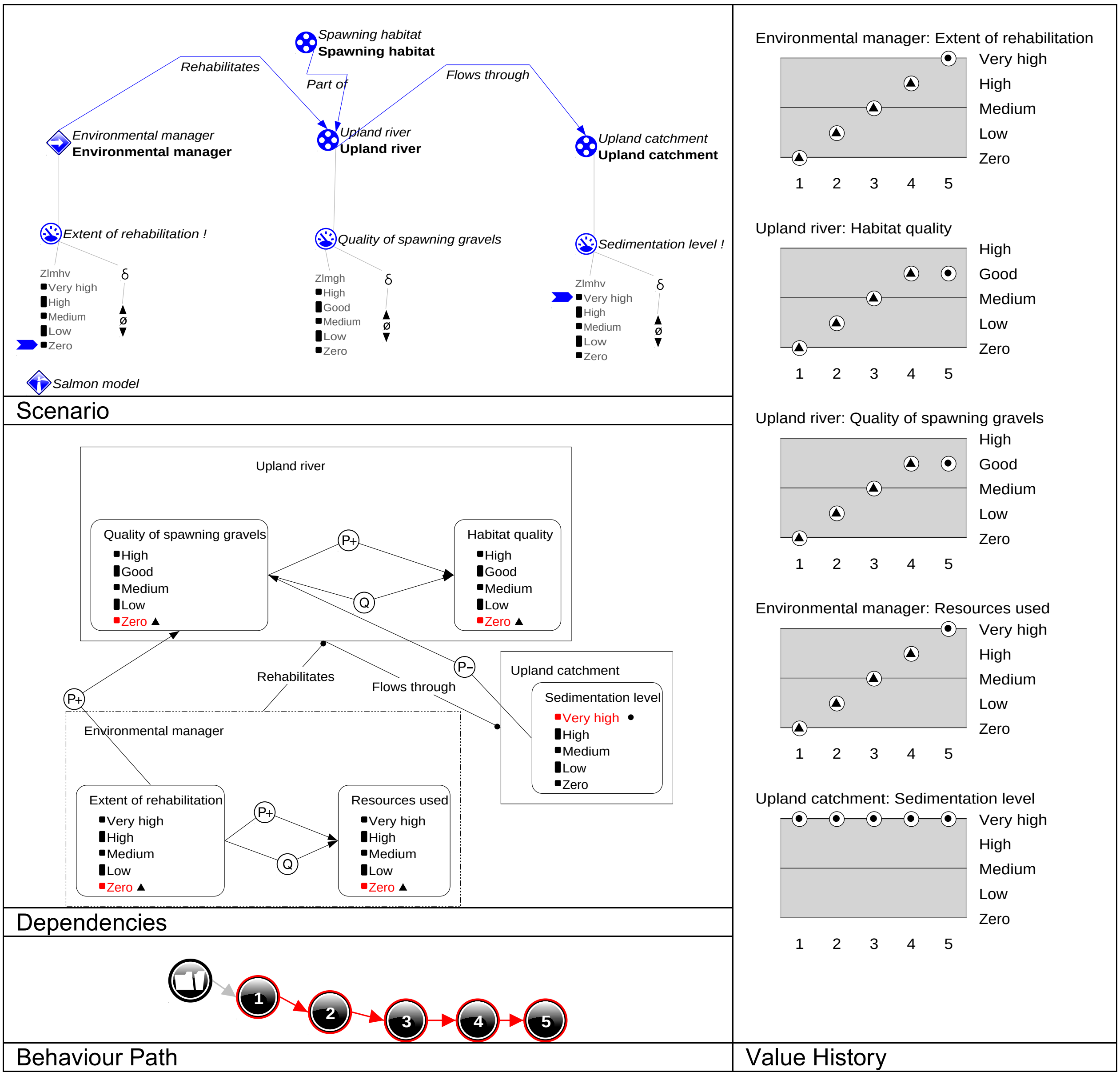


Figure 3.24 Outputs of the scenario “Extent of rehabilitation (gravel cleaning) increases from zero whilst Sedimentation level is Very high and steady”.

3.2.7 Angling and fisheries

One of the socio-economic factors considered in the UK case study is the benefit derived from angling. In the UK case study angling is represented as the entity *Fishery* which is a set of the entity *Angler*. Whilst fisheries for salmonid species have some different characteristics to that of a fishery based around coarse fish (of which bream is one example) they do have similarities that can be implemented in both models. Angling is implemented into the UK case study using five model fragments, four of which can apply to both models and one is specific to the River Trent salmon model (Figure 3.25).

The basic model fragment describing a fishery is model fragment Mf16. This fragment implements the concept that if there is a *Fishery* that *Exploits* a *Population* that *Consist of* the *Adult* life stage then two quantities *Number of anglers* and *Exploitation rate* are given to the Fishery. In this model exploitation rate is used to consider the relative sizes of the fishery in terms of number of anglers and the size of the stock they can exploit in terms of the number of adults recruited. To implement the basic concept that the *Exploitation rate* is determined by the relative size of the population (stock of fish available) and the size of the fishery, the rate is calculated by the calculation Number of anglers minus Number recruited. The rate also receives two proportionality relations P+ (*Exploitation rate*, *Number of anglers*) and P- (*Exploitation rate*, *Number recruited*). When exploitation rate is "plus" it indicates that fishing pressure exceeds the stock level (Number of adults) available to support it. When the rate is "minus" it indicates that the stock size is greater than the current fishing pressure and could support a higher number of anglers. When the rate is "zero" then the fishing pressure is in balance with the stock size.

The socio-economic value of angling can be seen as the economic revenue generated by the fishery and associated industries and also as the social well-being generated by the activity of fishing itself. This concept is modelled in fragment Mf17 where the quantity *Value* is added to the *Fishery* and is implemented as proportional to the number of anglers, P+ (*Value*, *Number of anglers*). The quantity value is also set using a directed correspondence from *Number of anglers* to *Value*.

Model fragment Mf18 implements a concept that the size of a fishery will grow in response to the size of the stock (number of adults) that is available for capture. In this model this concept is limited by the assumption label "Assume fishery grows in an under exploited fishery". This assumption allows the fishery to expand in size when the exploitation rate is "minus". If there is a fishery, its exploitation rate is minus and the assumption hold true in the scenario then the exploitation rate has an I- relation to Number of anglers, I- (*Exploitation rate*, *Number of anglers*). The concept is modelled in this way so that the fishery can grow in response to an under exploited fishery but that it may not necessarily shrink in response to reduced number of adults.

Model fragment Mf a10 implements the concept that the action of a Fishery manager can control the size of a fishery and prevent over exploitation of a population. The control of fishing effort as a directed influence I- from a "plus" *Rehabilitation rate* of a *Fishery manager* to the *Number of anglers* is limited to conditions when the fishery is over exploited (if *Exploitation rate* is "plus") and if the assumption that "Fisheries management controls exploitation" is explicitly set up in a scenario. The action of this model fragment is to keep the fishing effort in balance with the population size when the population size itself is decreasing.

Model fragment Mf19 implements a concept specific to the River Trent salmon model. This concept covers a fishery where the anglers remove the fish they catch and act as a source of mortality within the adult life stage. The model fragment denotes that in a model about salmon where there is a *Fishery* which is over exploiting the stock (*Exploitation rate* = plus) then there is a directed influence I- *Exploitation rate*, *Number surviving*.

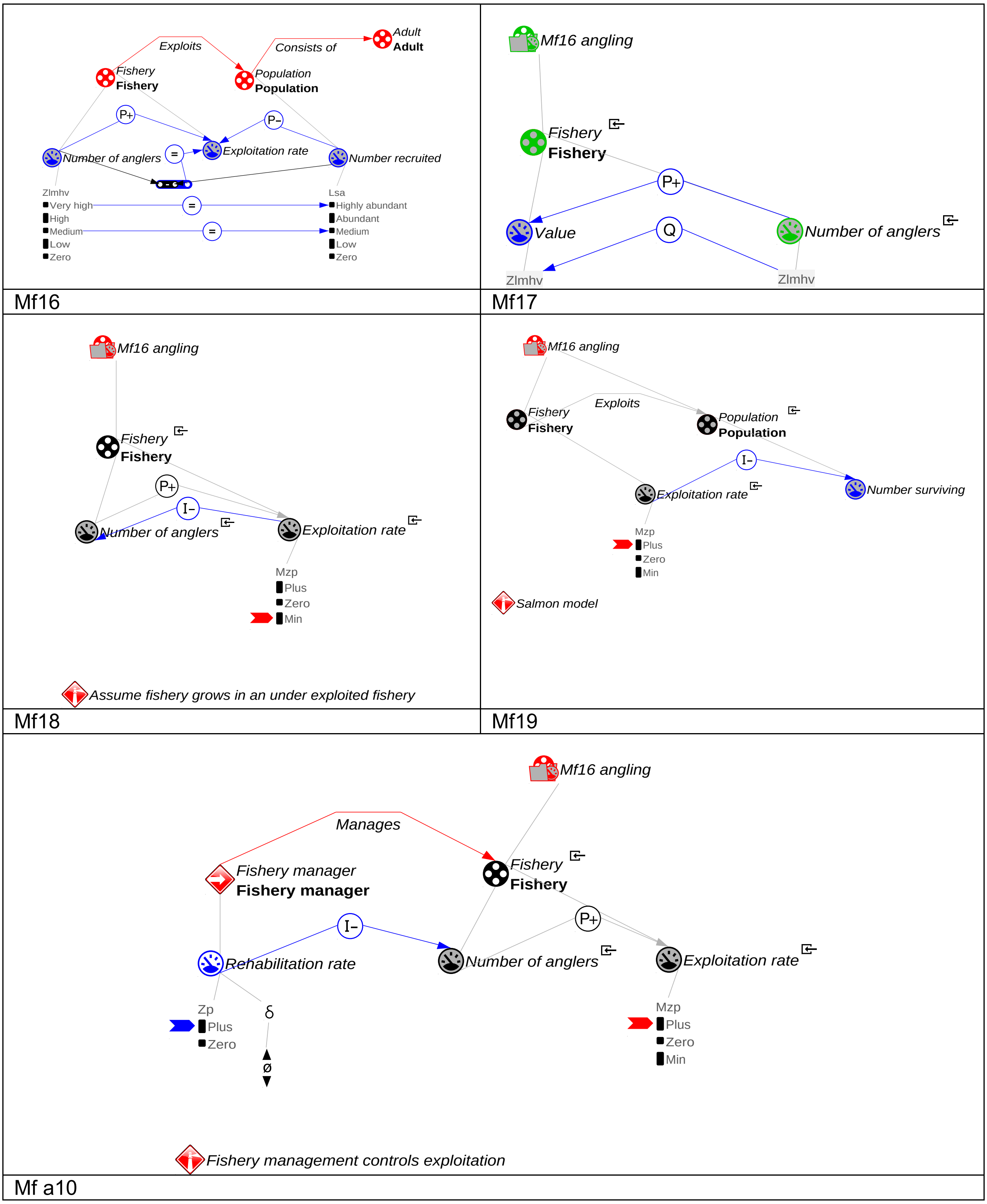


Figure 3.25 Model fragment relating to angling and fisheries exploiting a population of adult fish.

4 SPECIFIC INTEGRATED MODELLING SCENARIOS

4.1 Integrated scenarios – initial values

The design of the QR model for exploration of the UK case study allows for each concept to be modelled independently within simple scenarios and simulations. For example, as shown above the effect of changing habitat quality on the survival of a particular life stage can be simulated in isolation from the rest of the life cycle. However, the ultimate goal of such a model is to consider the effects of actions on one particular habitat or life stage on the whole life cycle and the consequences for the human elements to the system. Therefore, integrated scenarios were developed to look at the effects of rehabilitation on the whole life cycle following the generic scenario structure presented in Section 2. The integrated scenarios consider the effects of rehabilitation on habitat quality for a given level of a human activity (degradation agent). In all scenarios the *Extent of rehabilitation* is initially zero and an exogenous modelling behaviour is used to increase the extent of rehabilitation throughout the simulation until the extent reaches very high. Each integrated scenario has a minimum set of information that must be given for the simulation to be simulated correctly. The key factor in specifying a scenario is the consideration of the starting values for *Habitat quality* and the *Numbers surviving*. Within the River Trent salmon model the initial population size can be considered to be zero. In the Great Ouse bream model the initial values for the numbers of each life stage surviving must be carefully considered as the initial population size is greater than zero. As the rehabilitation model fragments determine the numbers recruited at each life stage from the numbers of the previous life stage surviving only the *Number surviving* needs to be specified in the scenario.

All life stages must be present connected in a loop from *Adult – Egg – Juvenile – Sub adult – Adult* using the *Recruits into* configuration. As a basic minimum each life stage must be specified to *Inhabit* its relevant River e.g. *Adult* salmon *Inhabits Lowland river*. Each river must have the quantity Habitat quality. If a particular life stage/habitat type isn't the focus of the model then the initial value for Habitat quality needs to be specified in the scenario (and given an exogenous "steady" behaviour). If the life stage is the focus of the model in the sense that the river/habitat it occupies is affected by degradation/rehabilitation then the habitat type must also be specified in the scenario e.g. *Spawning habitat* is *Part of* the *Upland river*. For rivers/habitats that are the focus of the scenario the initial value of the *Habitat quality* does not need to be specified as the model will calculate it from the values specified for the *Intensity* of activity of the *Degradation agent* and the *Extent of rehabilitation* of the *Environmental manager*. In all scenarios the *Extent of rehabilitation* is initially set to zero but given an exogenous increasing behaviour. The *Intensity* of the degradation agent is set to a specific value and given an exogenous "steady" behaviour.

In more complicated scenarios Immigration and Stocking can be considered using the assumption labels with a scenario specification. If immigration is considered than a neighbouring population must be specified to be close to the adult population. The neighbouring population needs to be given a plus *Straying rate* with an exogenous "steady" behaviour. If stocking is to be considered a *Fishery manager* must be specified to be linked to the juvenile population with the configuration "*Stocks*". The *Fishery manager* needs to be given the quantity "*Stocking rate*" with a plus value and an exogenous "steady" behaviour.

All scenarios for the River Trent model need the "Salmon model" assumption label specifying. Two examples of integrated scenarios are given here.

4.2 Scenario 1 – Trent S1 rehabilitation of lowland river connectivity (no immigration or stocking)

In the scenario "Trent S1 rehabilitation of lowland river connectivity (no immigration or stocking)" (Figure 4.1) only one habitat is rehabilitated influencing the *Habitat quality* and *Population potential* for adult salmon. Initial values for the Number surviving at each life stage is set to zero and for all rivers, other than the lowland river, the Habitat quality is set to "Good" with an exogenous "steady" behaviour. In this scenario no exogenous sources of recruitment are considered (neither stocking nor immigration) (Figure 4.1). The expected behaviour for this simulation is for the rehabilitation activity to improve the habitat quality of the Lowland river but for no change to occur in the population size because there is no source of recruitment for the population to be re-established (Table 4.1).

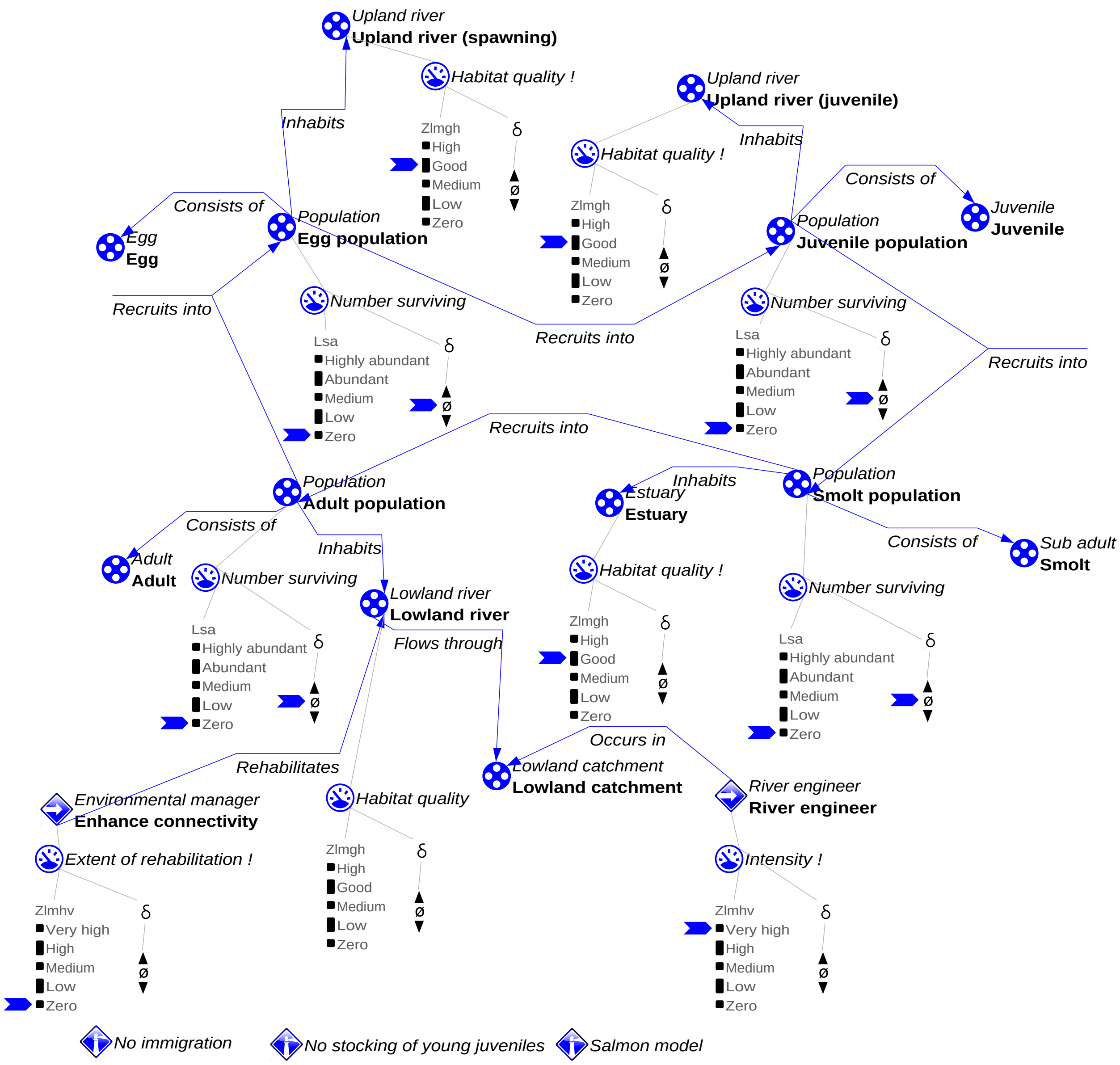


Figure 4.1 Scenario Trent S1 – rehabilitation of lowland river connectivity (no immigration or stocking).

Figure 4.2 gives the dependencies causing the behaviour in the simulation. The figure shows how the model adds in all the relevant quantities; such as *Quality of upstream connectivity*, *Number recruited*, *Net survival dynamic*, *Value* and *Resources used*; that were not specified within the scenario.

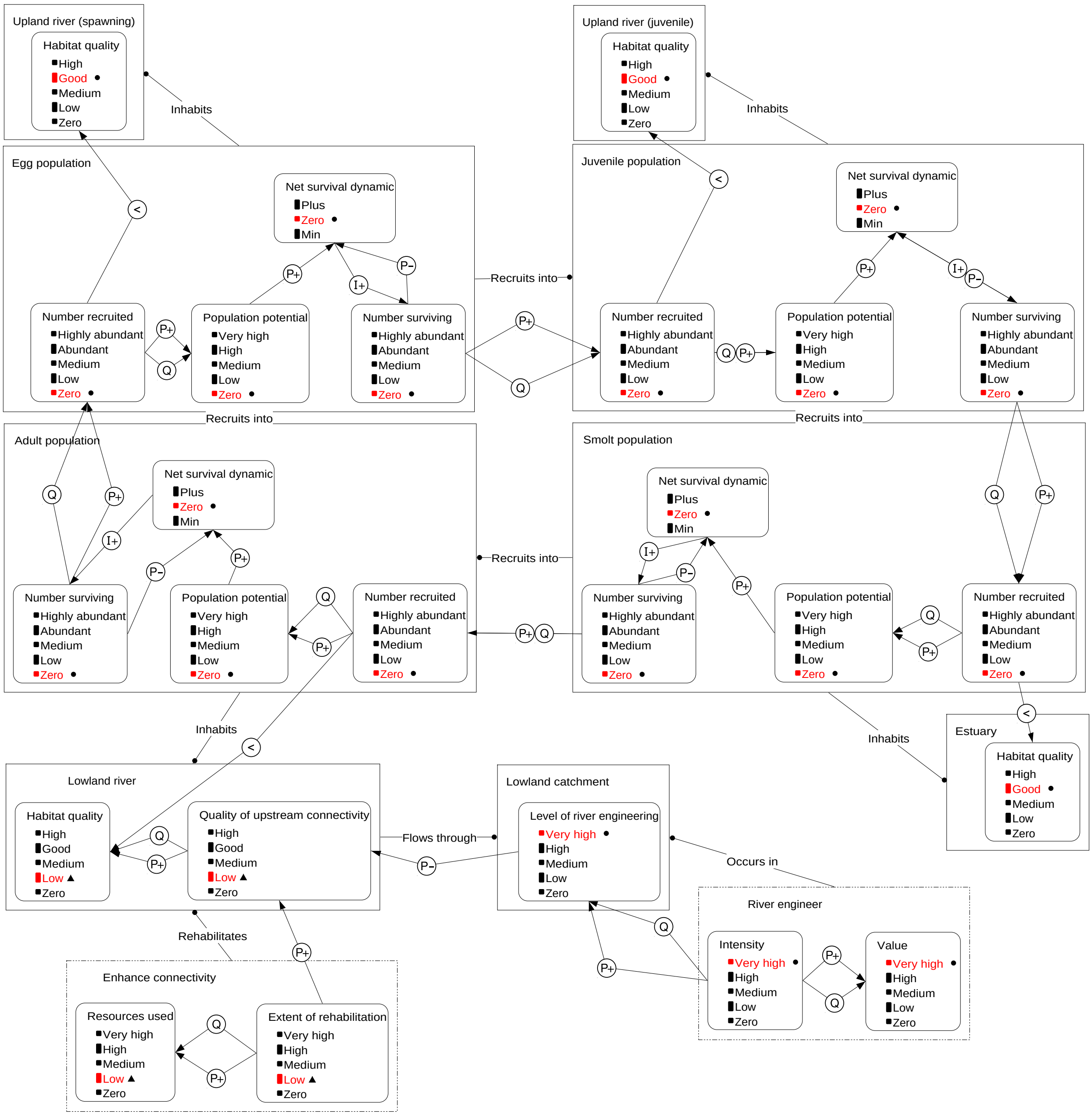


Figure 4.2 Dependencies in state [2] of the full simulation of scenario Trent S1.

Table 4.1 Summary of behaviour for the scenario “Trent S1 - rehabilitation of lowland river connectivity (no immigration or stocking”.

Scenario Name	Trent S1 - rehabilitation of lowland river connectivity (no immigration or stocking
Full simulation	5 states
Initial States	[1]
End states	[5]
Relevant behaviour path	[1, 2, 3, 4, 5]
Behaviour description	In state [1] The intensity of river engineering is high and the extent of rehabilitation is zero (increasing due to exogenous behaviour), therefore the Quality of connectivity is zero but increasing (due to the proportionality with the increasing rehabilitation). As the extent of rehabilitation increases the quality of connectivity increases (states [2, 3 & 4]). In the final state [5] the extent of rehabilitation is high but the quality of connectivity is only good, indicating the concept that even with intensive river engineering that the quality of connectivity habitats cannot be high when the sedimentation level is very high. As rehabilitation is undertaken the resources used increase to Very high in state [5]. As the population level is zero and there are no exogenous sources of recruitment (immigration or stocking) then the population does not re-establish and habitat improvement alone has not had the desired rehabilitation effect.

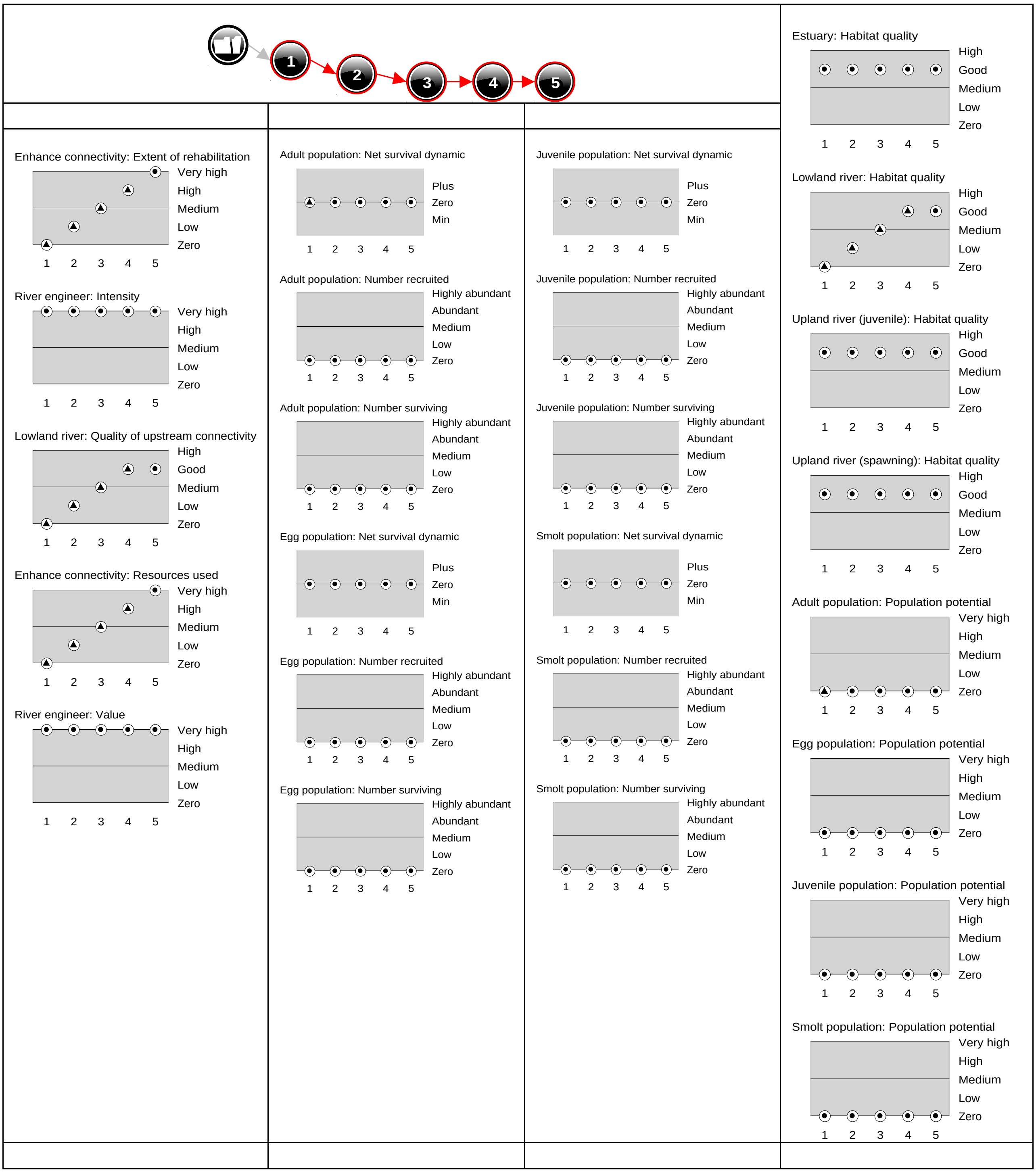


Figure 4.3 Simulation of scenario Trent S1.

4.3 Scenario 2 – Trent S2 rehabilitation of lowland river connectivity (stocking active)

In the scenario "Trent S2 rehabilitation of lowland river connectivity (stocking active)" only one habitat is rehabilitated influencing the *Habitat quality* and *Population potential* for adult salmon. Initial values for the Number surviving at each life stage is set to zero and for all rivers, other than the lowland river, the Habitat quality is set to "Good" with an exogenous "steady" behaviour (Figure 4.4). In this scenario stocking of juveniles by a Fishery manager is considered as an exogenous source of recruitment. The expected behaviour for this simulation is for the rehabilitation activity to improve the habitat quality of the Lowland river and for the juvenile population size to increase as the juvenile habitat quality is "Good". As the number of juveniles surviving increases so recruitment to smolts and adults increases and eventually the increased recruitment of adults and the improved connectivity of the lowland river allow an increase in the recruitment of eggs (spawning). Eventually a salmon population should establish with all life stages having High numbers surviving (limited by habitat quality being good).

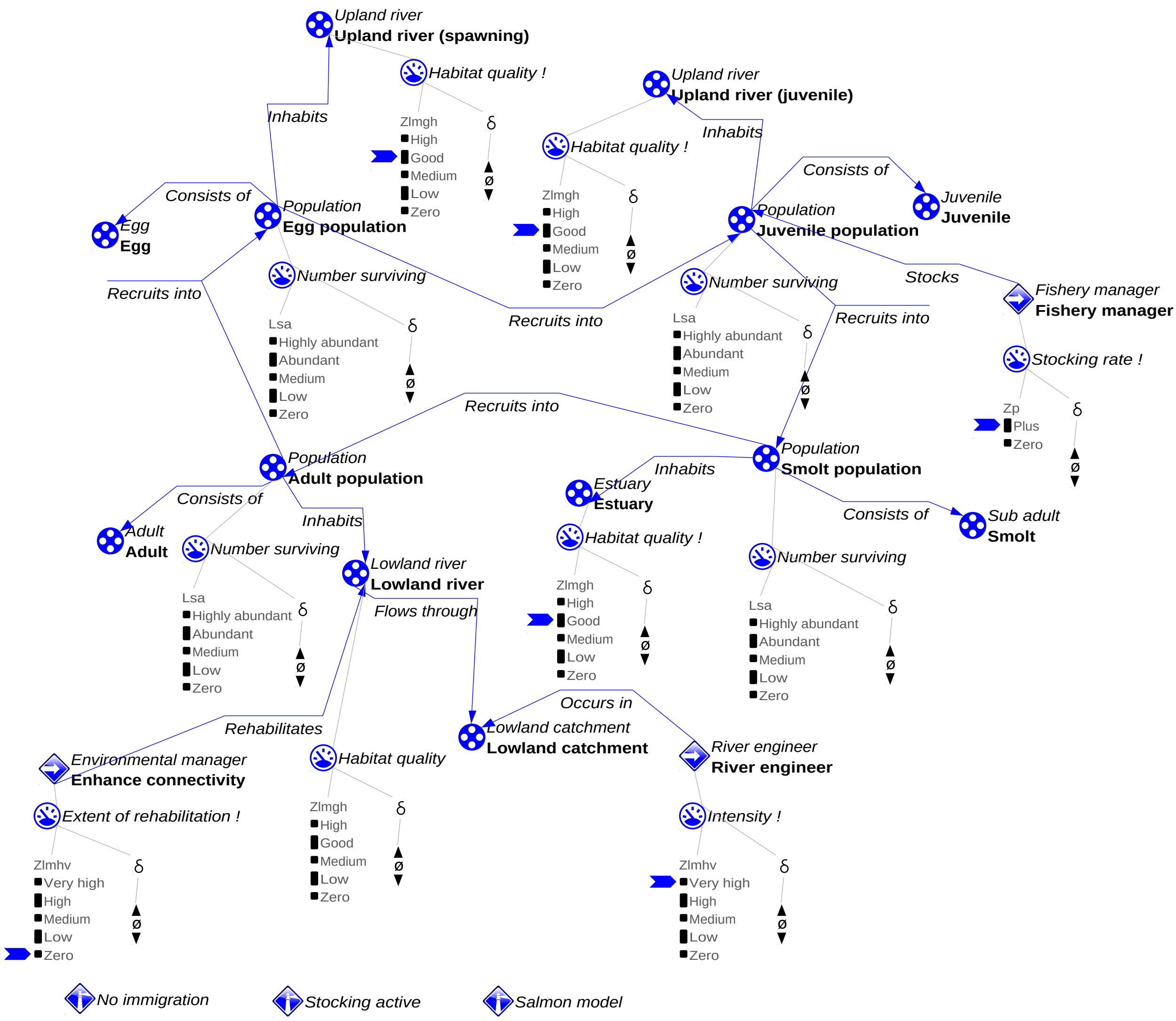


Figure 4.4 Scenario Trent S2 – rehabilitation of lowland connectivity (stocking active).

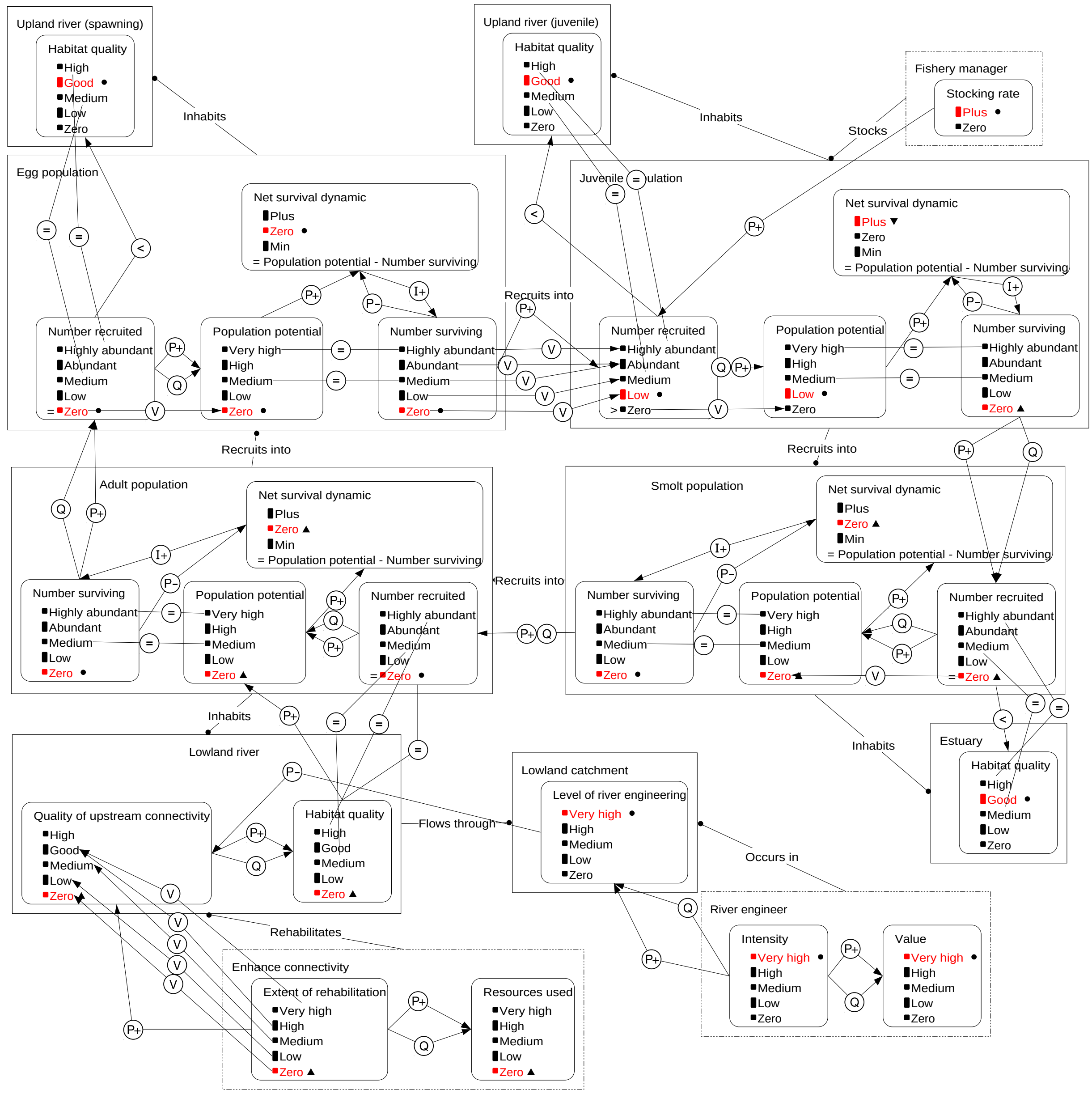


Figure 4.5 dependencies for state [1] in the simulation of scenario Trent S2 – rehabilitation of lowland connectivity (stocking active).

Unfortunately this integrated scenario is currently too complicated for GARP3 to simulate effectively as the engine tries to reason all possible combinations of quantity values and rates of change for *Number surviving*, *Population potential*, *Number recruited*, *Quality of spawning habitat* and *Extent of rehabilitation*. This problem is evident given that the simple scenario of a single life stage with increasing recruitment and decreasing habitat quality generated 78 states (Section 3).

4.4 Simple scenarios for two life stages

Given that the full life cycle scenarios are currently too big to explore within GARP3 simpler scenarios were developed to enable exploration of rehabilitation concepts. Therefore, scenarios were developed to look at the consequences of rehabilitation of specific habitats for specific life stages within the models for the Great Ouse and River Trent systems. These simple scenarios relate the rehabilitation activity to the habitat quality of a specific life stage, the survival within that life stage and the consequences for recruitment to the next life stage. Three example scenarios are shown here:

1) Adult bream scenario – the effect of the creation of floodplain waterbodies to mitigate for the effects of land drainage on the quality of habitats for adult bream.
2) Sub-adult bream scenario – the effect of rehabilitation of main channel habitats to mitigate for the effects of river engineering/channelisation on the quality of habitats for sub-adult bream.
3) Juvenile salmon scenario (no stocking) – the effect of rehabilitation of juvenile habitats in an upland river to mitigate for the effects of intensive abstraction of water on the quality of habitat for juvenile salmon.

All three of these scenarios are presented as the outputs from GARP 3 and an exploration of one of the relevant paths in the behaviour.

Scenario – adult bream scenario and creation of floodplain waterbodies

Table 4.2 Summary of behaviour for the “adult bream scenario and creation of floodplain water bodies”.

Scenario Name	“adult bream scenario and creation of floodplain water bodies”
Full simulation	46 states
Initial States	[1]
End states	[46]
Relevant behaviour path	[1, 2, 3, 5, 9, 13, 17, 29, 31, 44, 46] or any path from [1] to [46]
Behaviour description	In state [1] The extent of land drainage is high due to the intensity of human activity in the catchment and the extent of rehabilitation is zero (increasing due to exogenous behaviour), therefore the Abundance of floodplain waterbodies is zero but increasing (due to the proportionality with the increasing rehabilitation). As the extent of rehabilitation increases the abundance of floodplain waterbodies increases (states [2, 5, 5, 9 & 13]). In the final state [46] the extent of rehabilitation is high but the abundance of floodplain waterbodies is only high, indicating the concept that even with intensive rehabilitation that the abundance of floodplain waterbodies cannot be very high when land drainage level is very high. As rehabilitation is undertaken the resources used increase to Very high in state [46]. As the back waters are created by rehabilitation the Population potential for adults increases from zero to a maximum value of high by state [29]. As the Population potential increases the Net survival dynamic becomes plus indicating a capacity for an increase in the Numbers surviving. This causes the numbers surviving to increase until they match the population potential in state [46].

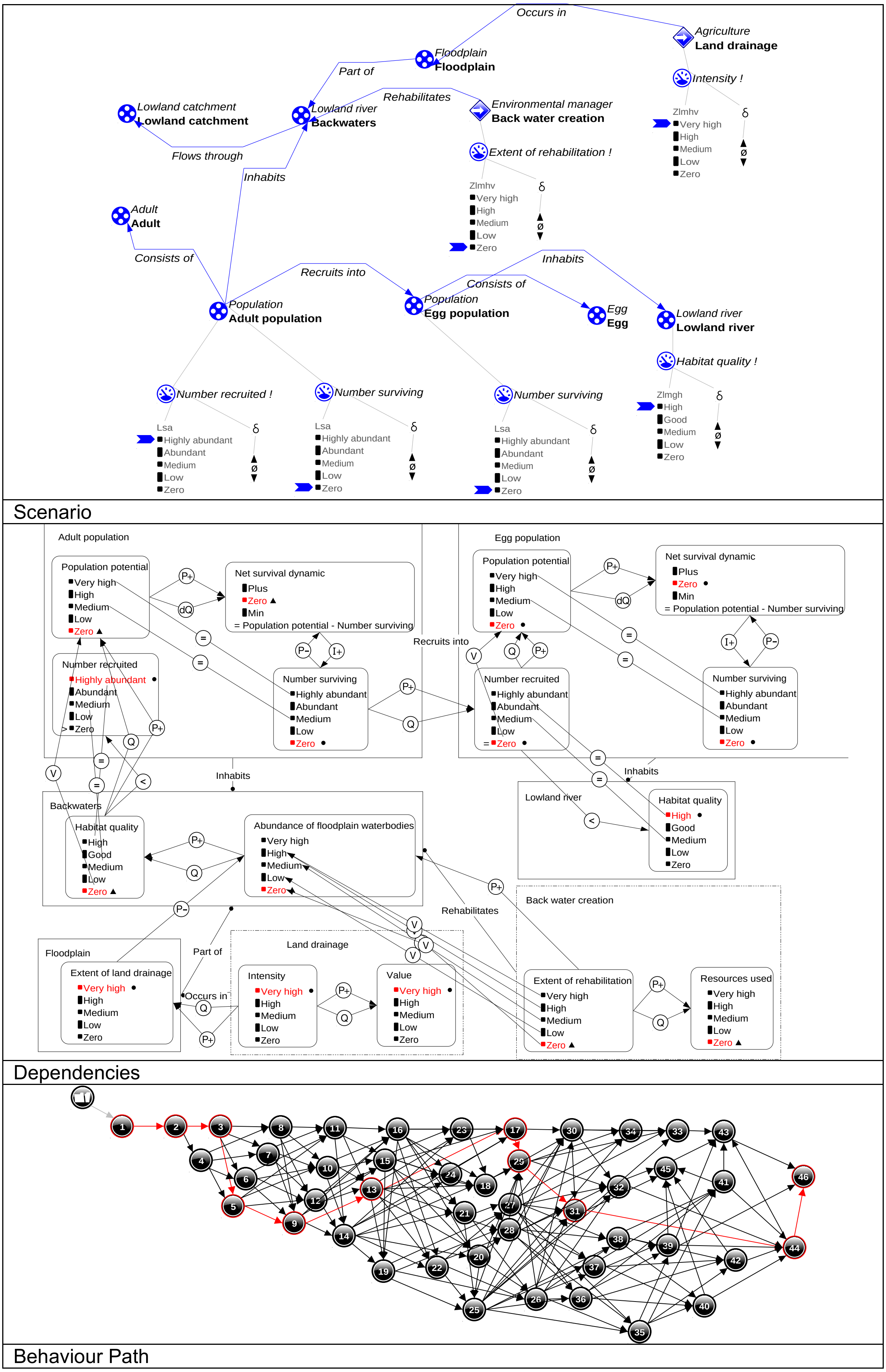


Figure 4.6 Outputs of the “adult bream scenario and creation of floodplain water bodies”.

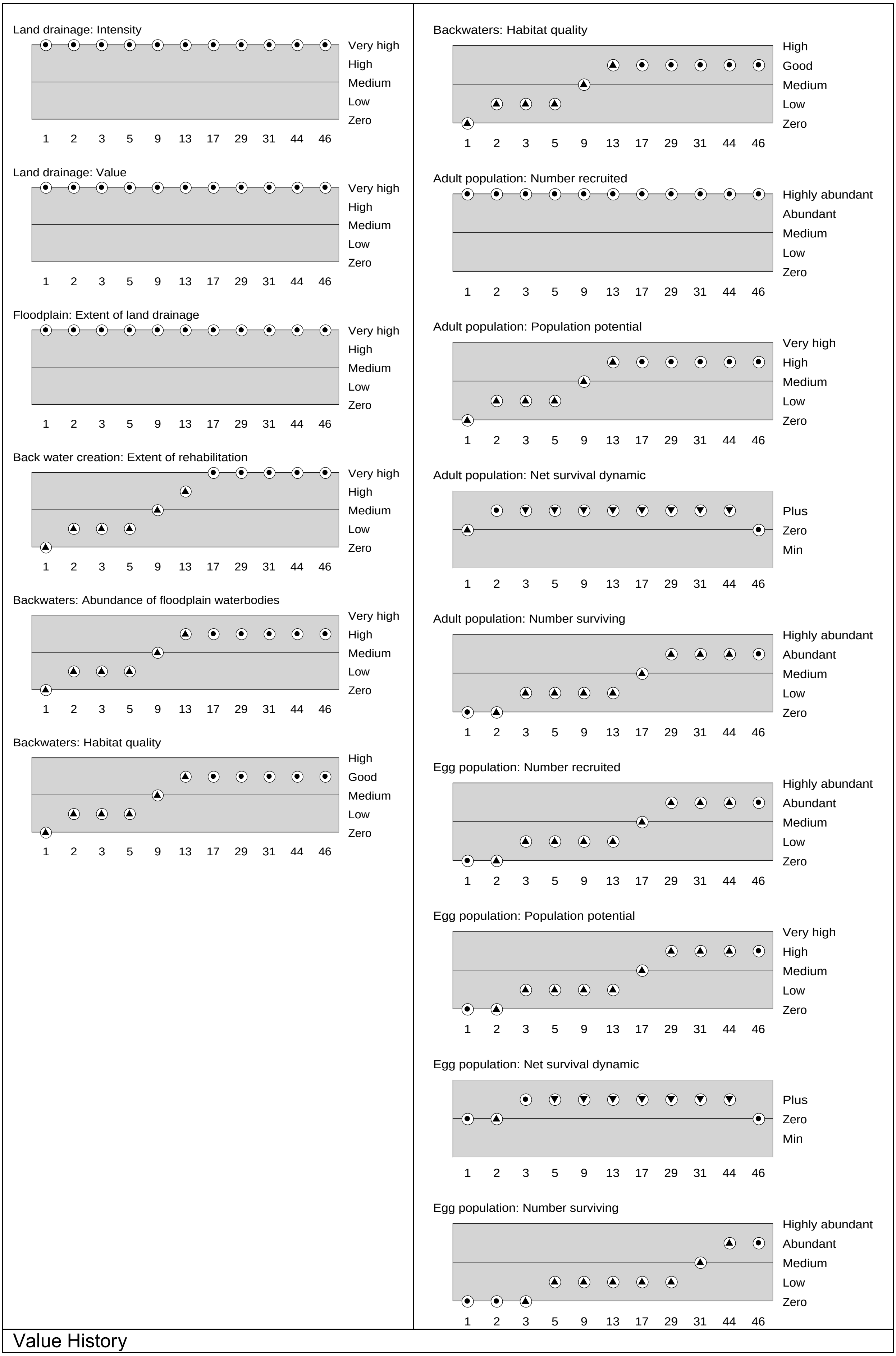


Figure 4.7 Outputs of the “adult bream scenario and creation of floodplain water bodies”.

Scenario – sub-adult bream scenario and rehabilitation of main channel habitats

Table 4.3 Summary of behaviour for the "sub-adult bream scenario and rehabilitation of main channel habitats".

Scenario Name	"sub-adult bream scenario and rehabilitation of main channel habitats"
Full simulation	46 states
Initial States	[1]
End states	[46]
Relevant behaviour path	[1, 2, 3, 5, 9, 13, 17, 29, 31, 44, 46] or any path [1] to [46]
Behaviour description	In state [1] The extent of channelisation is very high due to the intensity of river engineering in the catchment and the extent of rehabilitation is zero (increasing due to exogenous behaviour), therefore the quality of main channel habitats is zero but increasing (due to the proportionality with the increasing rehabilitation). As the extent of rehabilitation increases the quality of main channel habitats increases (states [2, 3, 5, 9 & 13]). In the final state [46] the extent of rehabilitation is very high but the quality of habitat is only high, indicating the concept that even with intensive rehabilitation that the quality of main channel habitats cannot be very high when river engineering is very high. As rehabilitation is undertaken the resources used increase to Very high in state [46]. As the quality of main channel habitats is improved by rehabilitation the Population potential for sub-adults increases from zero to a maximum value of high by state [17]. As the Population potential increases the Net survival dynamic becomes plus indicating a capacity for an increase in the Numbers surviving. This causes the numbers surviving to increase until they match the population potential in state [46]. The increase in the numbers of sub-adults surviving is transferred into an increase in the number of adults recruited.

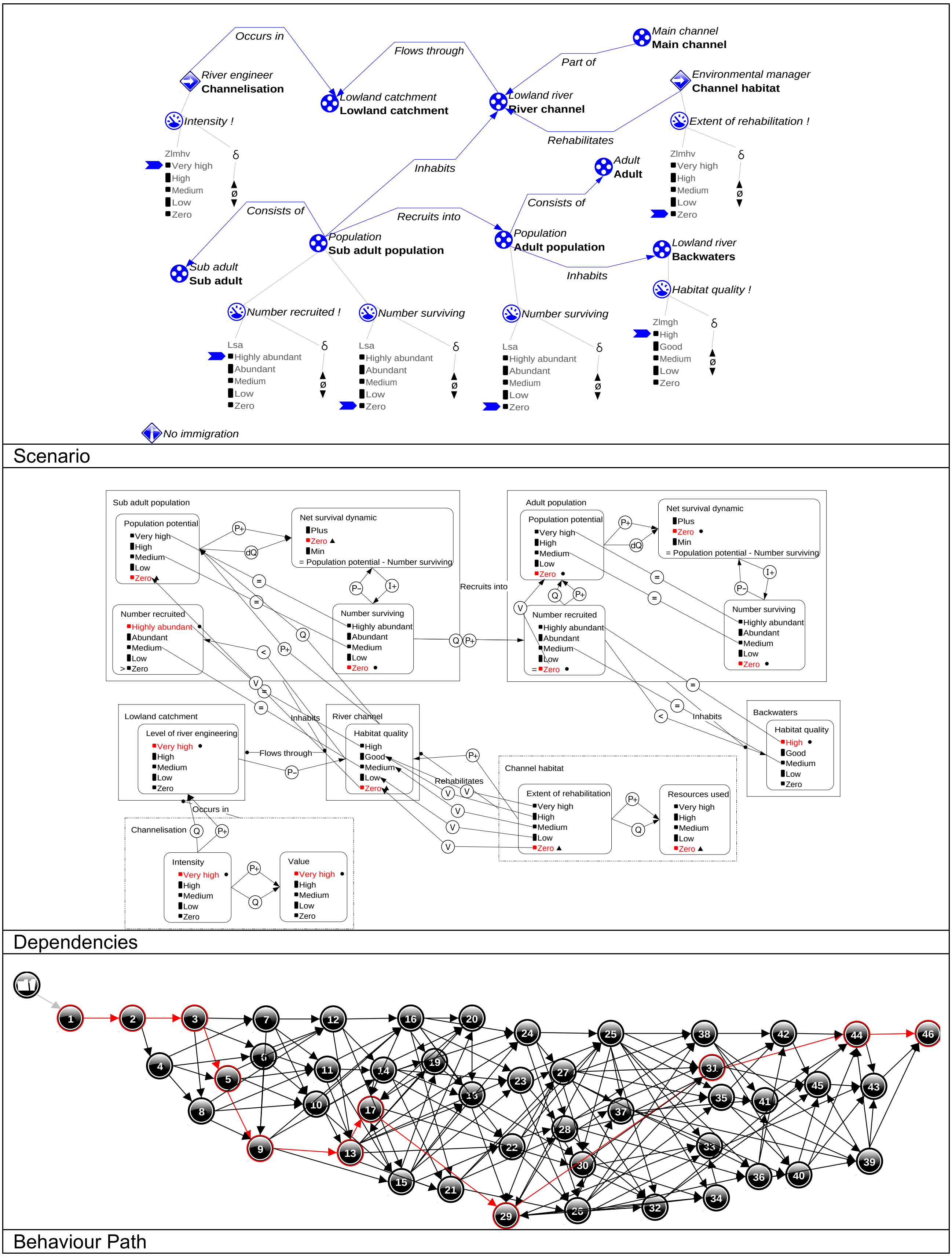


Figure 4.8 Outputs of the “sub-adult bream scenario and rehabilitation of main channel habitats”.

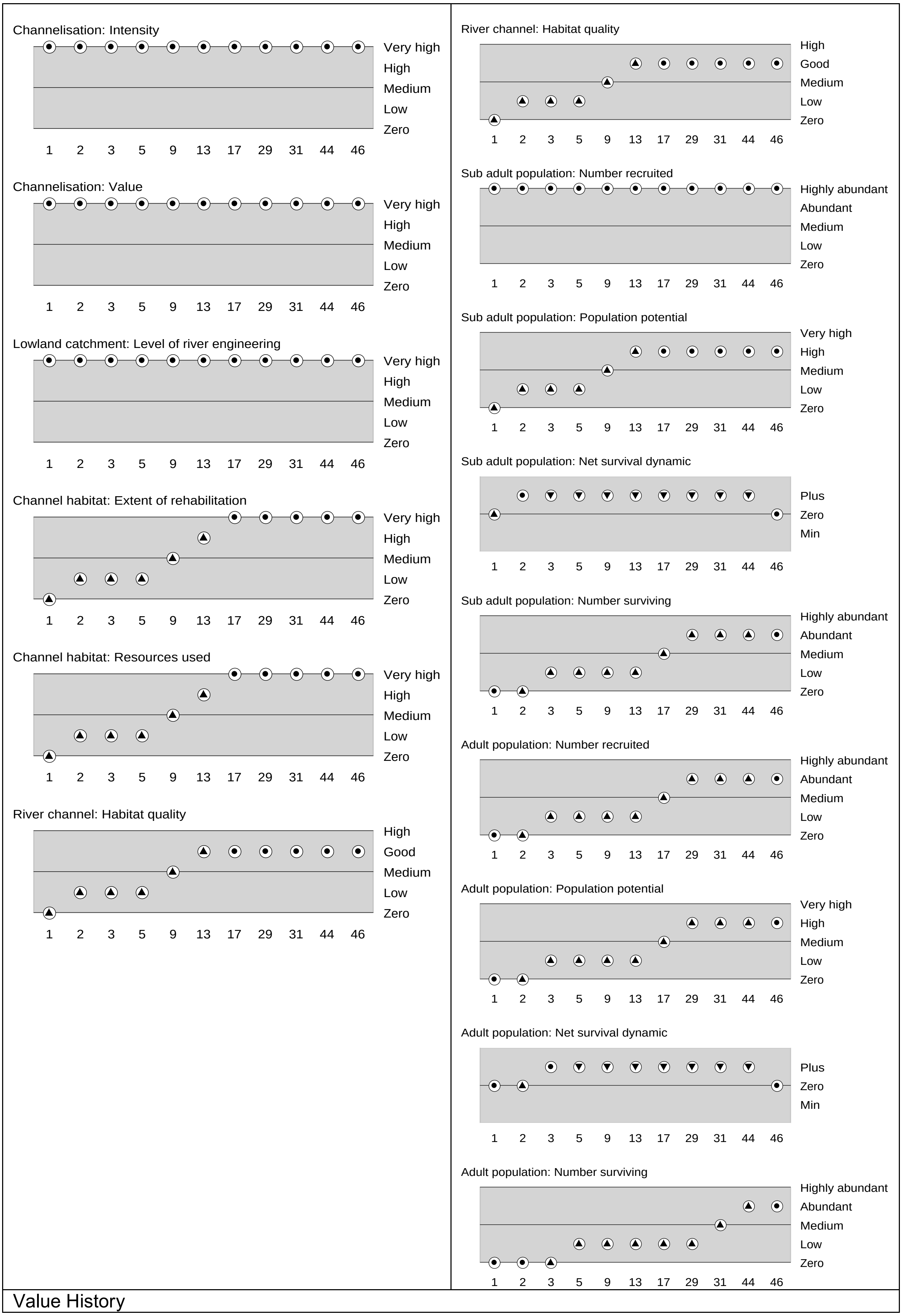


Figure 4.9 Outputs of the “sub-adult bream scenario and rehabilitation of main channel habitats”.

Scenario – juvenile salmon and rehabilitation of juvenile habitats

Table 4.4 Summary of behaviour for the “juvenile salmon and rehabilitation of juvenile habitats” scenario.

Scenario Name	“juvenile salmon and rehabilitation of juvenile habitats”
Full simulation	[46]
Initial States	[1]
End states	[46]
Relevant behaviour path	[1, 2, 3, 5, 9, 13, 17, 29, 31, 44, 46] or any path [1] to [46]
Behaviour description	In state [1] The amount of water abstracted is very high due to the intensity of the water industry in the catchment and the extent of rehabilitation is zero (increasing due to exogenous behaviour), therefore the quality of juvenile salmon habitats is zero but increasing (due to the proportionality with the increasing rehabilitation). As the extent of rehabilitation increases the quality of juvenile habitats increases (states [2, 3, 5, 9 & 13]). In the final state [46] the extent of rehabilitation is very high but the quality of juvenile habitat is only high, indicating the concept that even with intensive rehabilitation that the quality of juvenile habitats cannot be very high when abstraction is very high. As rehabilitation is undertaken the resources used increase to Very high in state [46]. As the quality of juvenile habitats is improved by rehabilitation the Population potential for juvenile salmon increases from zero to a maximum value of high by state [17]. As the Population potential increases the Net survival dynamic becomes plus indicating a capacity for an increase in the Numbers surviving. This causes the numbers surviving to increase until they match the population potential in state [46]. The increase in the numbers of juveniles surviving is transferred into an increase in the number of smolts recruited.

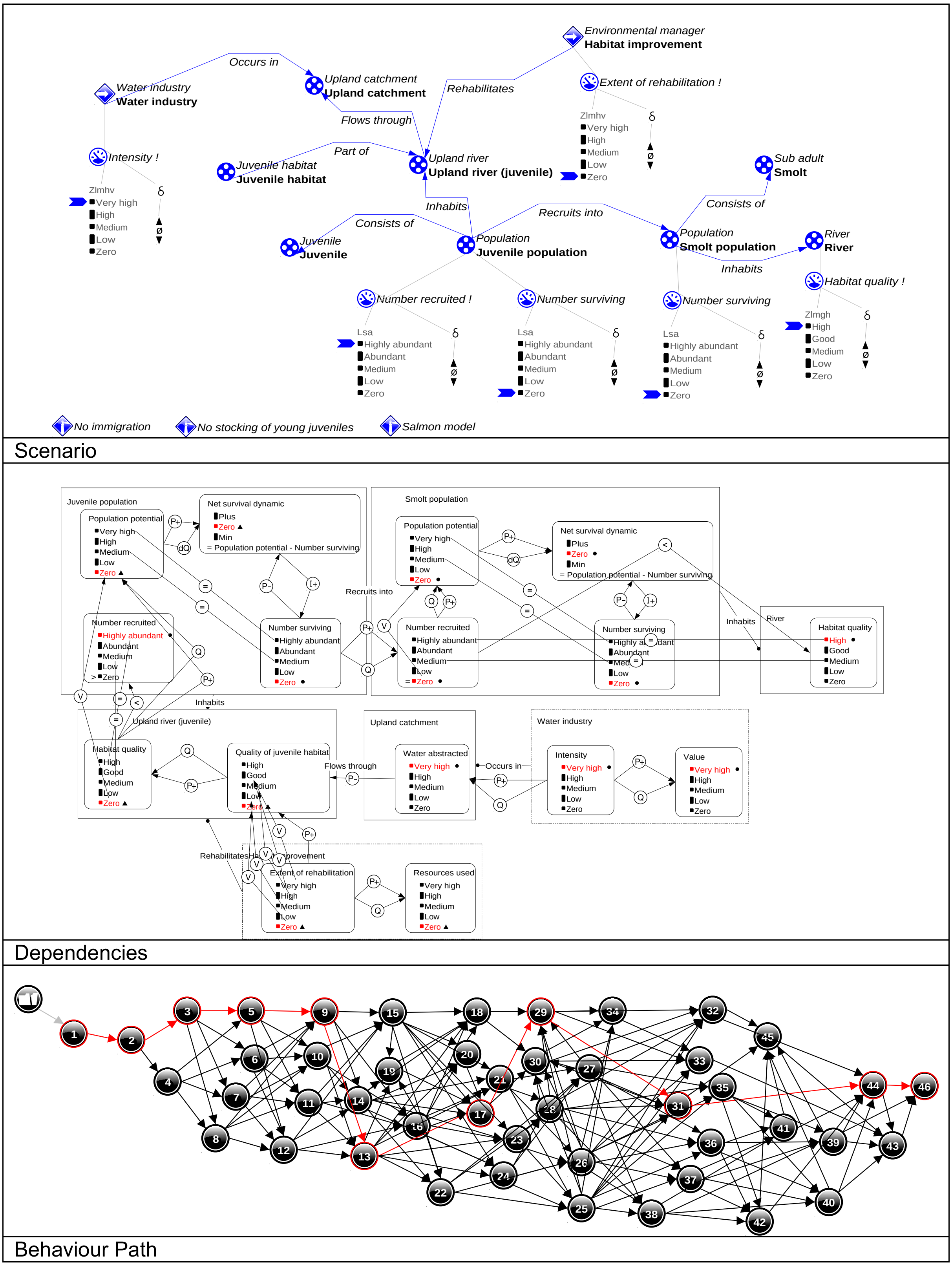


Figure 4.10 Outputs of the “juvenile salmon and rehabilitation of juvenile habitats” scenario.

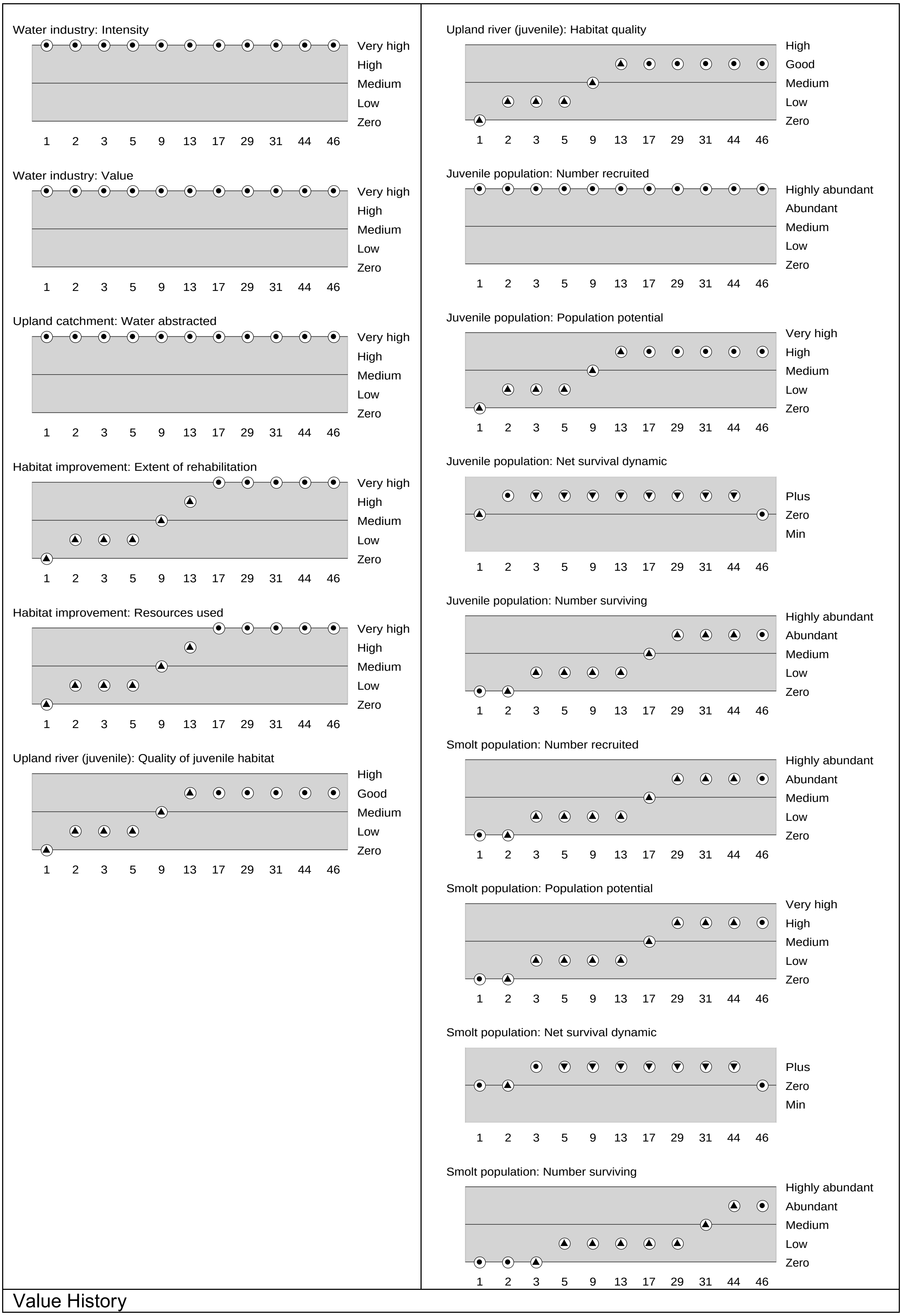


Figure 4.11 Value history outputs of simulation of the "juvenile salmon and rehabilitation of juvenile habitats" scenario.

4.5 Scenario and simulation issues

Whilst the model implemented in GARP 3 to explore the UK case studies has included most of the concepts detailed in the textual description of the case study (Noble & Cowx 2006), and is 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) are 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. Despite this the model produced does allow for the concepts detailed in the textual description of the model to be explored using simple scenarios.

At present the model only allows for scenarios and simulations to be run exploring the effect of increasing extents of rehabilitation activities on the quality of a habitat affected by a set intensity of a human activity that has a degradation effect. An improved version of the model could allow for both the extent of rehabilitation and the intensity of a degradation activity to have dynamic behaviours within a model whilst still retaining limitations on the quality of habitat based on the quantity and behaviour of these two factors.

The concept of the costs of and resources used by rehabilitation has been implemented in the model using a simple correspondence between the resources used and the extent of rehabilitation. However, in the scenarios this only translates to identifying that as the extent of rehabilitation increases due to the exogenous influence that resources are used. A more detailed and complicated approach could be to model the use of resources by rehabilitation so that the resources available for rehabilitation are used up by the rehabilitation activity and that rehabilitation activity stops once the resources that were available are exhausted. In such an approach the extent of rehabilitation could then somehow be limited by the resources that are available. This would allow for more complicated scenarios where economic and social resources become a limiting factor to rehabilitation and sustainable management of environments.

5 CONCLUSIONS AND FURTHER MODELLING

5.1 Model implementation

The implementation of the model into the GARP environment lead to a number of changes to the proposed model design and as such the implementation lead to the model evolving from its original constructs. In particular the representation of a number of the key concepts changed in response to exploration of the simulation produced during development. In many cases the changes related to differences in relation to how concepts where represented as entities or quantities within the model. One of the fundamental changes was the change from representing life stages as quantities belonging to a population entity to life stages being modelled as individual entities. This meant that life stages were represented as individual populations which made up the population as a whole. This change from representing life stages as entities rather than quantities meant that many concepts relating all life stages could be implemented in single model fragments that are applicable to all life stages.

One of the key changes from the initial planning to the final model was the handling of the concepts of mortality and survival within a life stage. The original attempts to implement the model were based around balancing competing mortality and survival (or recruitment) rates at each life stage, where each life stage was represented as a quantity. In the original plan for implementing the model mortality and survival would directly influence the numbers of each life stage through competing I+ and I- relationships. Conceptually this required that when the numbers of a life stage was in balance with the limits for the life stage (based on numbers of the previous life stage and the habitat quality) that the I- influence from mortality and the I+ influence from survival would be in balance and hence the number of the life stage would be steady. In situations where the number of a life stage was greater or less than the limit for that life stage then mortality rate would exceed or be exceeded by the survival rate causing the numbers of the life stage to decrease or increase respectively. However, this approach proved difficult, particularly in terms of generating continuous behaviours. Conceptually, it was difficult to model scenarios where mortality was initially in balance with survival, through a simulated behaviour where population size changes due to increased/decreased mortality/survival to another steady state situation where the number of the life stage matched it potential value (based on habitat quality and numbers of the previous life stage) and mortality rate was again in balanced with survival rate. Even with the fundamental change in the modelling of life stages as entities rather than quantities, which itself allowed the separation of the concept of survival within a life stage (mortality) and between life stages (recruitment), did not allow easily modelling of mortality and survival as competing rates which affect a population size. The final solution to this problem was to isolate recruitment as a process and to give each life stage four fundamental quantities: 1) the *Number recruited*, 2) the *Number surviving*, 3) the *Population potential* and 4) a *Net survival dynamic*. The four quantities could be used to represent the key life stage processes albeit in an abstract form. The derivation of the abstract quantity, *Population potential*, allowed modelling of the possible population size (represented by Number surviving) based upon the limit for the population based on the original number of individuals entering the life stage (*Number recruited*) and the prevailing *Habitat quality*. The balance between the maximum possible population size and the actual number surviving then was represented by the *Net survival dynamic* which acted as an abstracted representation of mortality/survival rates combined into a single variable. This representation allowed a single variable to control the changes in the number surviving, allowing both increases and decreases in magnitude and also simulation in which the number surviving could move from one steady state to another (i.e. allowing number surviving to rebalance with an altered population potential.

Another of the changes in the implementation was the representation of habitats and habitat qualities. Modelling each life stage as a population, and hence having generic model fragments for all populations, meant that to a certain extent that generic model fragments were required for the relationship between habitat quality and the population potential for a life stage. As such the representation of catchments, rivers and specific habitat types meant that model fragments could be described that related populations to a generic quantity called "*Habitat quality*". These generic model fragments could be then utilised in specific settings for different life stages and in different case studies by relating them to specific habitats/life stages/habitat qualities. This style of modelling allows for individual concepts within the case study to be explored in isolation, for example in the test scenarios which considered single populations without considering specific elements such as life stage or habitat type. This should enable the model to be explored at different complexities making the model suitable for exploration by a number of different users with different levels of back ground knowledge.

One of the key challenges in the implementation of the model was the development of model fragments which controlled the magnitudes of quantities in different situations. Such quantity limitations were required for *Population potential* (where the quantity was limited to the lower value of either *Habitat quality* or *Number recruited*) and for *Habitat quality* (where this was controlled by the intensity of human pressure on the habitat and the extent of rehabilitation). These two situations were modelled using different approaches. In the case of *Population potential* the quantity was limited using correspondences (between quantity spaces) from whichever of *Habitat quality* and *Number recruited* was the limiting quantity in any given situation. However, in the case of Habitat quality this was done by means of direct value correspondences from the *Extent of rehabilitation,* the construction of which were different at different levels of intensity of human pressure on habitats. These two alternative approaches were required as in the case of Population potential a single quantity was limiting whereas in the case of Habitat quality the initial quantity which was set by the intensity of human pressure was altered by the extent of rehabilitation. These two implementations gave different levels of flexibility in scenarios and simulations. The modelling of Population potential allowed for dynamic behaviour of both Habitat quality and Number recruited (including both increasing and decreasing in any scenario). The modelling of habitat quality itself was more restricted and only allowed simulations where the pressure of human activity on the habitat was at a fixed level and the extent of rehabilitation increases from zero. This limited flexibility in the implementation of habitat quality means that there is limited scope to explore human activities in the current model. Ideally an alternative implementation to limit the quantity of habitat quality would allow exploration of the full range of possible dynamic behaviours.

5.2 Scenarios and simulations

The QR model building approach allows systems and scenarios to be explored by integrating small elements of knowledge constructed as individual model fragments. This approach also allows complicated systems and scenarios to be explored by end-users by de-constructing the complex scenario into its individual components and by constructing simpler scenarios to explore individual concepts within the system. In this case study the complicated species life cycle was too large to simulate effectively. However, scenarios can be simulated to investigate the effects of rehabilitation on habitat quality for a particular life stage and the consequences for survival within a life stage and on the recruitment to the next life stage. This means that users cannot explore concepts such as bottle necks in rehabilitation plans e.g. where the proposed rehabilitation does not address a key issue at a later life stage which would limit improvement in population size. However, whilst the full original scenarios developed could not be simulated, this elemental approach still allows an end user to explore the concepts of rehabilitation and the ideas behind the factors that limit the performance of fish populations within river systems.

At this stage the implementation of the model limits the scenarios and simulations to those of habitat rehabilitation increasing due to exogenous behaviour in a situation of a fixed intensity of human degradation activity. Ideally a more dynamic model implementation would allow scenarios which examine the effect of increasing/decreasing intensity of human pressure on the ecosystem. Such model implementation would allow a greater exploration of sustainability issues over and above those of mitigating the effects of human activity through rehabilitation of riverine habitats.

5.3 Comparison of models

Whilst the Great Ouse and the River Trent are different river systems and the models are based around different species they do share similar concepts and principles. As such the two systems were modelled using the same approach to capture the common concepts to rehabilitation and sustainable management of rivers. Indeed the scenarios for the Great Ouse can apply equally to the lowland sections of the River Trent which suffers from similar human impacts on floodplain habitats. The main difference in the two systems, and how well the model reflects the true situation, lies in the ecology of the two indicator species that are being considered. In the River Trent system salmon are used as an indicator species for the quality of the river. This diadromous species has relatively discrete and specialised habitats for it different life stages and as such the modelling situation where each life stage is limited to a specific habitat type (and hence limited by the quality of that habitat) forms quite a good representation of the system. In the salmon model the habitat for each life stage is often spatially distinct so the implementation where a life stage has zero survival when the habitat quality of that habitat is zero is a suitable representation of the system. However, in the lowland Great Ouse model common bream are used as the indicator for lowland river quality. However, in the bream model, where the habitats are represented as main channel, marginal and back water, life stages are not really limited on only one of them, although in natural conditions one of those habitats is optimal and preferred habitat for a life stage. For example, in the Great Ouse model habitat for adult bream is limited by the quality of flood plain habitats. Whilst the floodplain waterbodies are the preferred habitat for adult bream, the life stage can also make use of the main channel if floodplain waterbodies are absent or limited. Additionally, spawning can occur in marginal areas of the river or in floodplain waterbodies. As such the representation of the Great Ouse is slightly more abstracted from the true situation than the River Trent salmon model. Further modelling for the Great Ouse lowland floodplain model could allow for the habitat quality for each life stage to be calculated as a combination of the qualities of the specific habitat types. For example the quality of habitat for adult bream could be calculated from the quality of the main river channel habitat and the quality of the backwater habitat. In such an approach the derivation of the general habitat quality could give equal weighting to each specific habitat type or it could give more weighting to the specific habitat type that is optimal for that life stage e.g. connected back water habitats for adult bream. To model a system where the *Population potential* for each of the life stages is set by a combination of the level of recruitment and habitat quality for that life stage based on a number of habitat types (e.g. floodplain and main channel habitats) would require some way of modelling the relative contributions of optimal and sub-optimal habitats.

5.4 Further modelling and issues

The scenarios and construction of model fragments for determining the quality of habitat, based on the balance of the extent of rehabilitation and the degradation intensity, are limited to exploring the effects of changing the extent of rehabilitation (using exogenous behaviours). The use of a suite of model fragments determining the correspondence from the value of the extent of rehabilitation to the habitat quality, one model fragment for each value of the intensity of a degradation activity, is a fairly rigid solution for implementation of the table of allowable values shown in section 3. As a result the model only copes with dynamic behaviour in the quantity *Extent of rehabilitation* in scenarios and simulations. Ideally an optimal model for exploration of these issues would allow for the exploration of dynamic behaviour in both aspects of human activity. Such a dynamic model would allow increases or decreases in the intensity of human degradation activities to be considered. Such a dynamic implementation is not easily achieved as a balance is required between the modelling of trends and behaviours (P+, P-, I+, I- etc.) and the modelling of quantity limitations using value correspondences or similar modelling constructs. The current model implementation relies heavily on value correspondences between points and intervals within quantity spaces and it is probably this that limits how dynamic the model can truly be. For example, different value correspondences are applied at different values of *Intensity* of human activity (see tables of allowable values), and in some situations correspondences between points and intervals change properties in adjacent quantity spaces of *Intensity* of human activity. As such this may cause discontinuous behaviours or inconsistencies when *Intensity* is given a dynamic rather than a steady behaviour in a simulation.

The use of value correspondences between quantity spaces, and specifically the differences in relating points to intervals and vice versa raises issues about the design of quantity spaces in ecological models. Ideal design of quantity spaces in models requires that points within a scale are true point values rather than pseudo-intervals. For example, in the 5-class quantity spaces in this model the only true point is zero whereas low, medium, good, high, very high etc. could be considered as either intervals or points. Ideally all these should be interval (with the possible exception of values like “medium”) and that points between these intervals should represent true thresholds between qualitative values. This would be an important improvement in the model as points and intervals are treated differently in the logical reasoning and makes potentially large differences in simulations depending whether value correspondence are made point-to-point, point-to-interval, interval to point or interval-to-interval. Identification of true points in ecological systems is generally difficult and often are just nominal thresholds between two intervals e.g. boundary between good and moderate status in an ecological assessment. However, it should be noted that the model already produces large simulations for even the simplest scenarios based around only one or life stages and more complicated quantity spaces whilst potentially enabling more dynamic behaviour would produce much larger more complicated simulation outputs.

In the scenarios and simulations the level of rehabilitation is controlled using exogenous behaviour to increase the extent of rehabilitation from zero to very high. This exogenous behaviour generates behaviours in habitat quality depending on the intensity of human activity that is set in the scenario. However, this representation limits how much different levels of rehabilitation could be explored in a number of models. Ideally a model would be able to explore how resources can limit the amount of rehabilitation that can be undertaken within any given situation, and the benefits that might be gained (similar to qualitatively exploring cost-benefit analysis). Therefore, rather than the simple implementation where the cost/resource used increases as the extent of rehabilitation increases, a system could be modelled so that a rehabilitation activity used up resources until there were no resources left available. In such a situation the extent of rehabilitation activity could be limited by the resources available. However, such an approach may require complex modelling limiting the relative changes in the use of resources to the amount of rehabilitation that is achieved. If this is not carefully modelled, any representation of rehabilitation as a rate that decreased resources available and increased the extent of rehabilitation would always include a behaviour path where the extent of rehabilitation increased to its maximum value not matter what the starting value for the amount of resources was. Such an unconstrained model would therefore produce extremely complex simulations.

One of the concerns for rehabilitation, particularly where conservation or re-population of a threatened species is concerned, is the source of individuals that will enable the population to re-establish. Re-establishment of a population can be considered from three sources; a residual population that has the capacity to expand through high fecundity, natural immigration of individuals from a neighbouring population or from stocking. This model attempted, with limited success, to model the influence of stocking and immigration on population recovery. In both cases this was modelled as an additional effect on the relationship between the numbers surviving from a previous life stage and the number recruited to the next. For example, stocking was modelled as an activity that slightly increased the number of juveniles recruited depending on the numbers of eggs that survived. However, the implementation of stocking and immigration in this way caused problems in behaviours, especially in life cycle scenarios. Therefore, any further adaptation to the model should consider these issues and attempt to find an improved solution for there implementation.

The current model was implemented such that the general *Habitat quality* of the *River* was controlled by one specific factor or one specific quality linked to the life stage or life stage habitat it was related to. Whilst this allows scenarios to be simulated concerning the key factors influencing each life stage, in reality the overall habitat quality (and hence mortality) for a life stage is controlled by a number of factors e.g. abstraction, sedimentation and water quality all relate to habitat quality for spawning habitats of salmon. Further developments of the model could include the determination of the habitat quality for the life stage to be determined from a number of specific quality factors. These could be implemented either equally using a worst case scenario where the general habitat quality takes on the value of the worst case of the specific quality factors e.g. if water quality was low and quality of spawning habitat was medium then the habitat quality for that river would be low. Alternatively the factors may be able to be combined in such a way that they may have different impacts for different life stages. For example, both sedimentation and abstraction effect spawning and juvenile habitat quality, but it can be considered that sedimentation has a greater effect on spawning habitat than it does on juvenile habitat. A modelling approach that relates the specific factors to general habitat quality differently for different life stages would produce a dynamic and diverse model allowing exploration of the effects of combined habitat factors and human activities.

One aspect of the model that is not fully developed and explored is the relationship of the salmon fishery with the fish population and the rehabilitation measures. The model fragments and implementation presented here are initial ideas and have not been fully developed within specific scenarios. Therefore, this is one aspect of the model that requires further consideration to be able to generate scenarios that may look at the socio-economic benefits to the fishery that can be derived from rehabilitation efforts.

The final model produced focuses clearly on the impacts of rehabilitation of rivers on fish populations and in addition, a certain extent the bottle necks that should be considered in rehabilitation programmes. For example, these bottle necks include the relative impacts of different human activities on different life stages and also the limitations of resource availability to rehabilitation activities. As such the model is very much focussed on the mitigation of the impacts of human activities on rivers. To explore further sustainable development issues in this context the model could be expanded to consider in more detail the social and economic factors of human activities. As such differences in sustainable and unsustainable activities could be considered rather than merely looking at rehabilitation after mitigating the negative environmental consequences of an unsustainable activity.

5.5 Conclusions

The final model presented here has been successfully implemented in terms of modelling the ecological processes of a fish population and how these processes relate to human activities and the targets and objectives of river rehabilitation for fish. Whilst the final model is too complex to allow easy modelling of the full life cycle within a rehabilitation scenario, simple scenarios based around pairs of life stages can be used to explore the key concepts related to population dynamics and river rehabilitation. In this context the model integrates the concepts of rehabilitation targeting specific habitat quality problems to remove survival bottlenecks within a population together with the cost of rehabilitation and the value that human activities have both in social and economic terms. As such this allows users to explore and consider the basic concepts of river rehabilitation.

Further model development could potentially focus in two directions. Firstly, the model could be re-developed to allow a greater dynamic flexibility in the behaviours it can produce using the existing concepts and information implemented within the model fragments. Alternatively, secondly, it could be further developed to include more specific concepts regarding the social and economic factors of river rehabilitation. Modifications and improvements to the implementation of the current concepts and information would allow scenarios which explore both the behaviour following rehabilitation and the behaviour of the system in response to increasing human pressure and activity. Whereas, modification and expansion of the model to include more specific social and economic concepts of the costs and benefits of rehabilitation and of human activities which may impinge on rivers would allow scenarios to be developed that can explore in detail qualitative cost benefit analysis of different sustainable and unsustainable activities.

Overall, the model presented here meets the majority of the modelling objectives and makes a good contribution to the development of qualitative modelling in the field of ecological modelling and representation of sustainable development issues.

6 REFERENCES

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7 APPENDIX 1

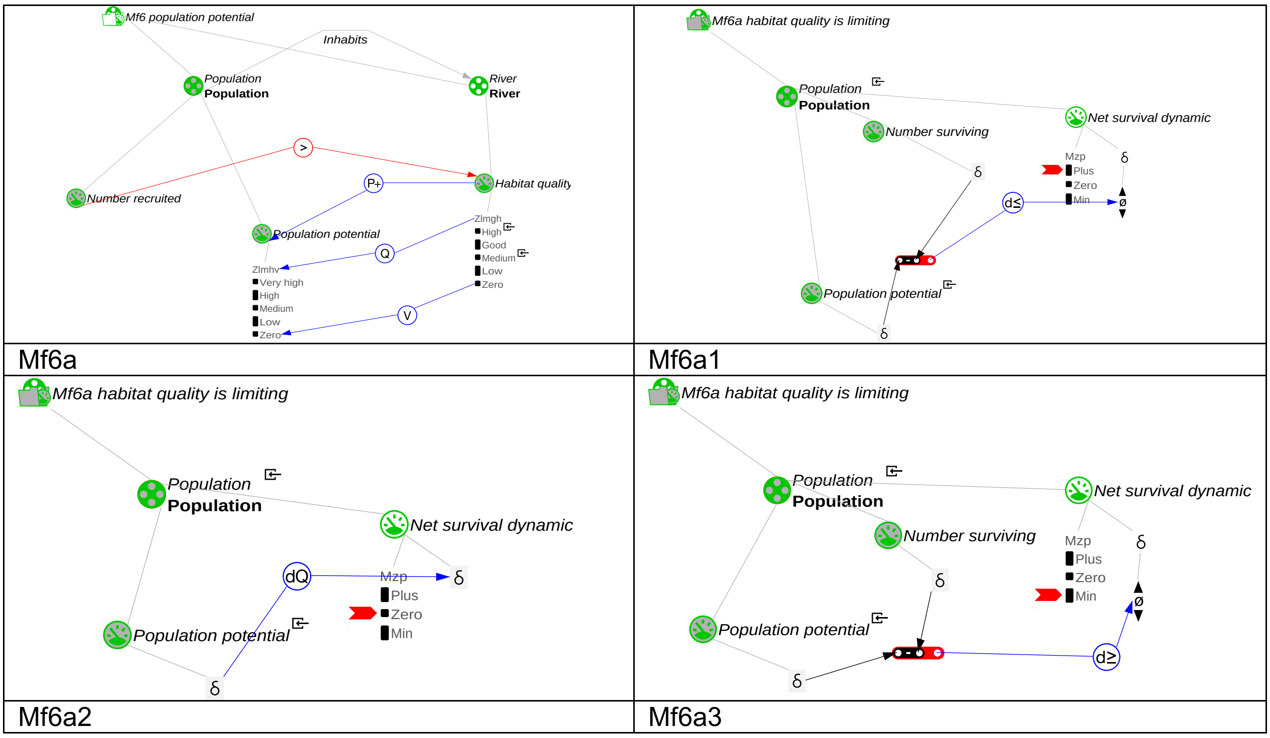

Figure A.1 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6a (*Number recruited* > *Habitat quality*) determines the *Population potential*.

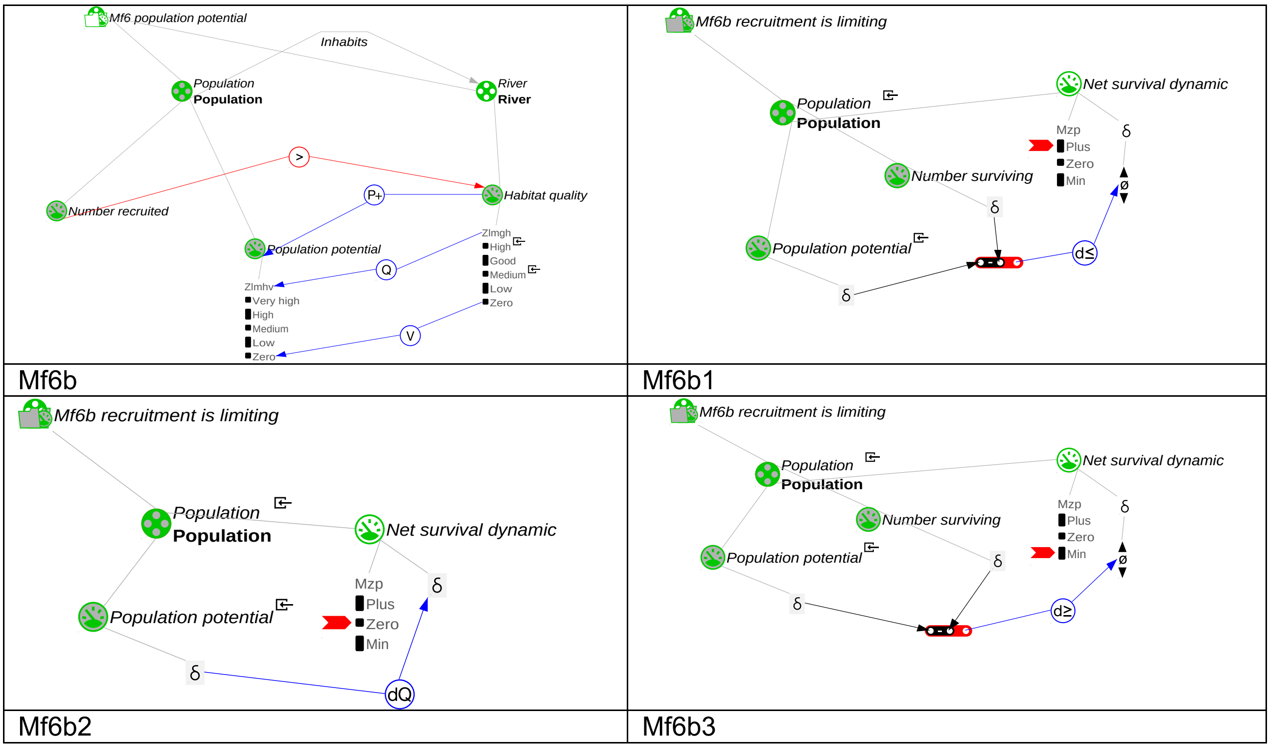

Figure A.2 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6b (*Number recruited* < *Habitat quality*) determines the *Population potential*.

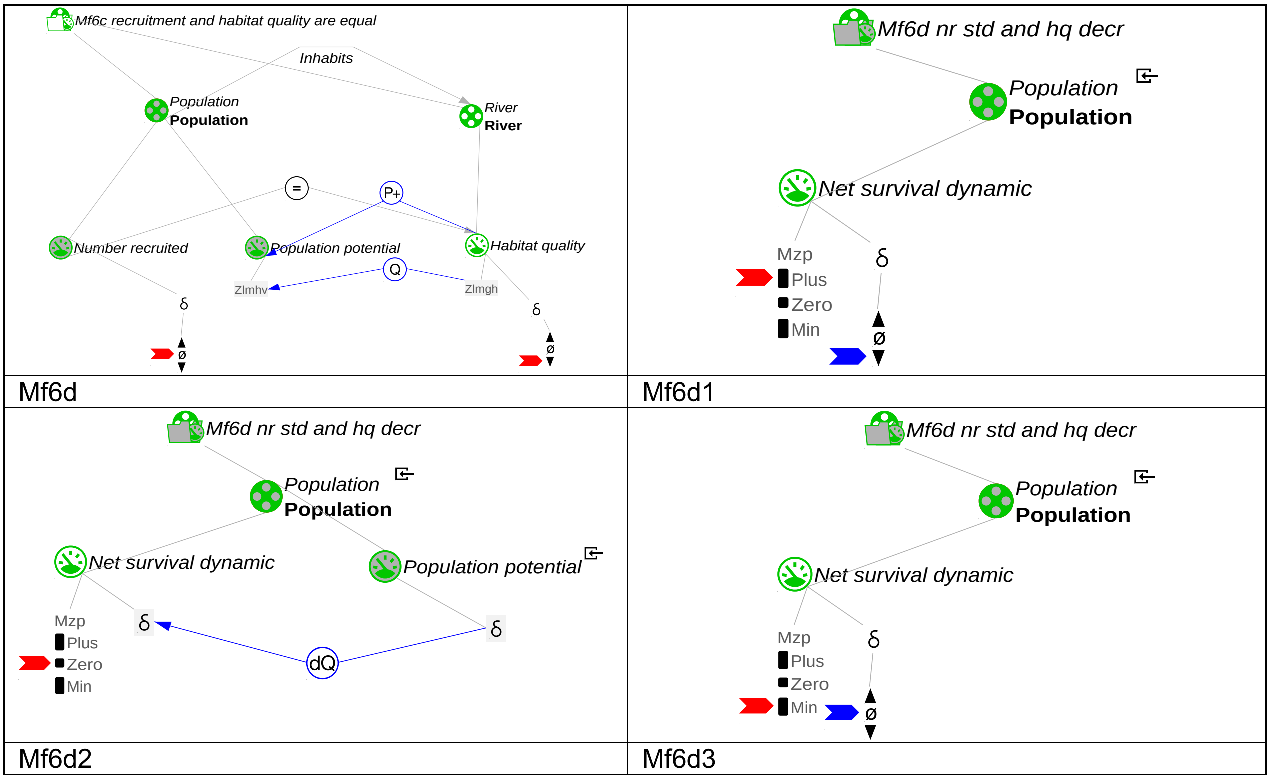

Figure A.3 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6d (*Number recruited = Habitat quality*) determines the *Population potential*.

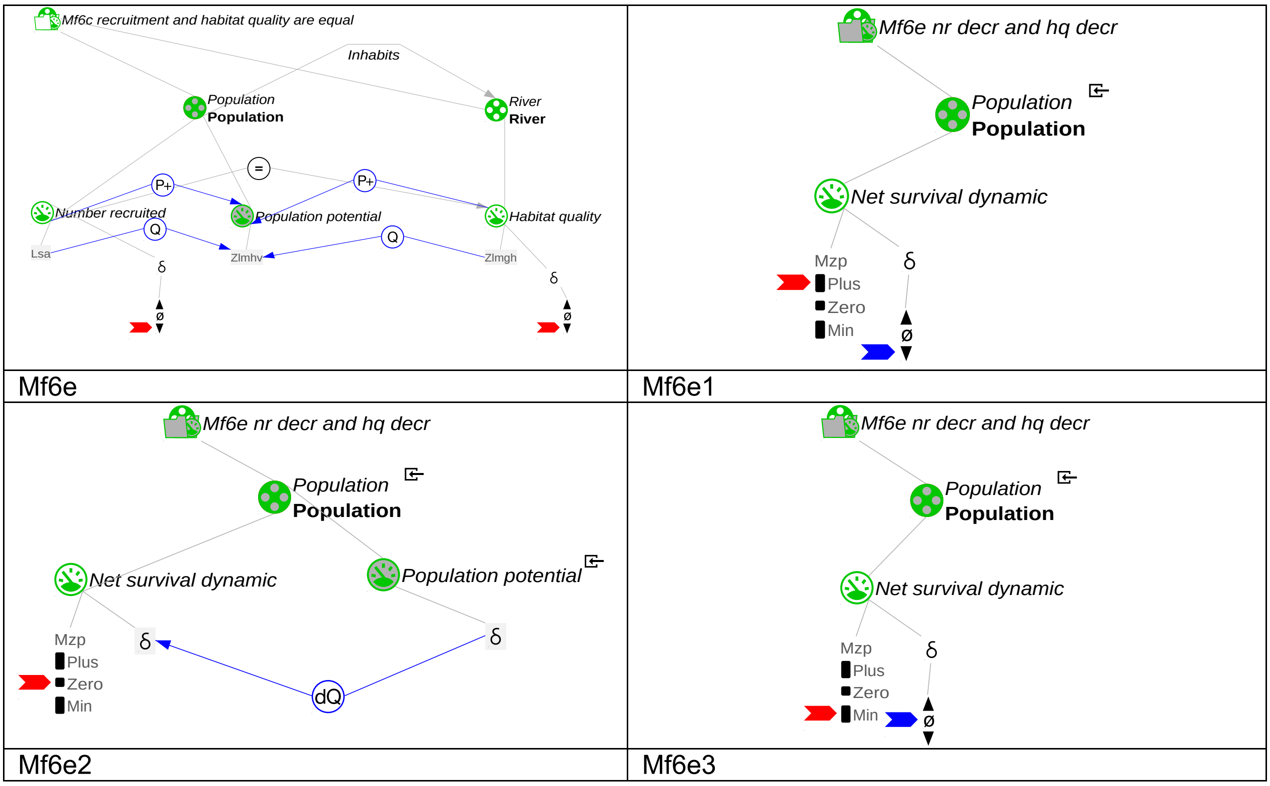

Figure A.4 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6e (*Number recruited = Habitat quality*) determines the *Population potential*.

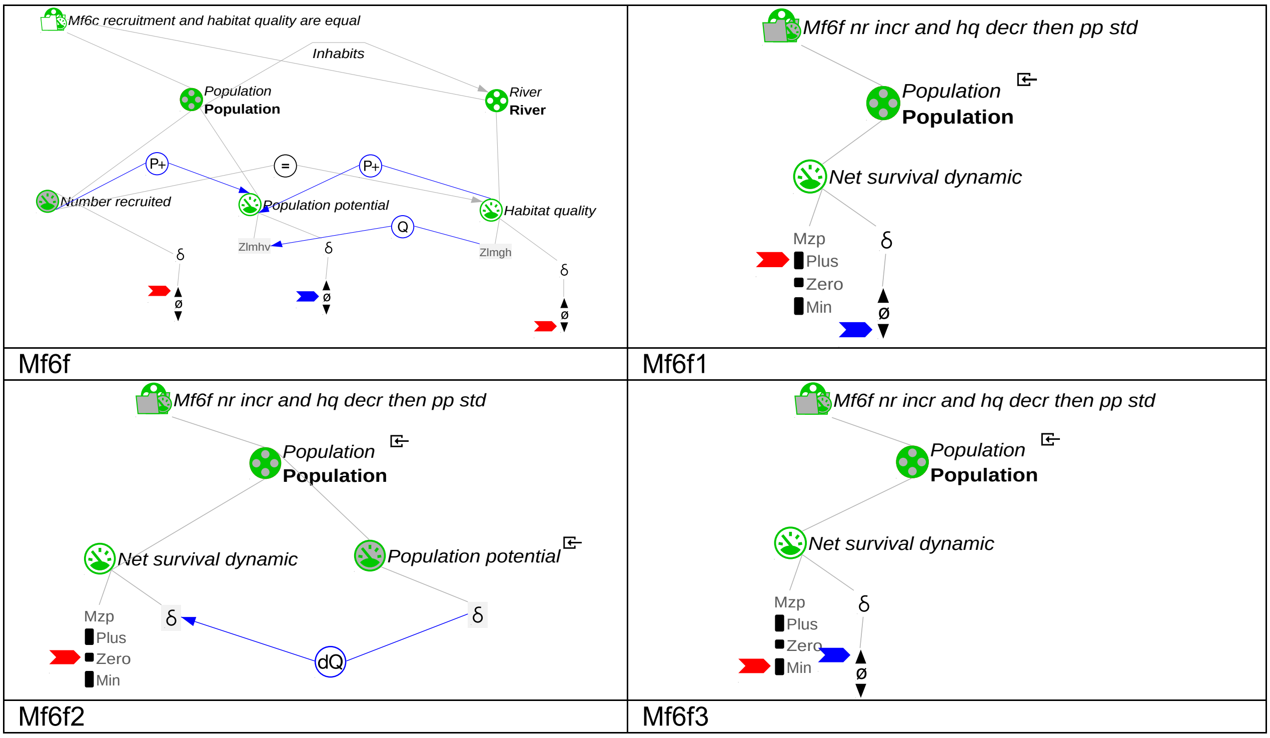

Figure A.5 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6f (*Number recruited* = *Habitat quality*) determines the *Population potential*.

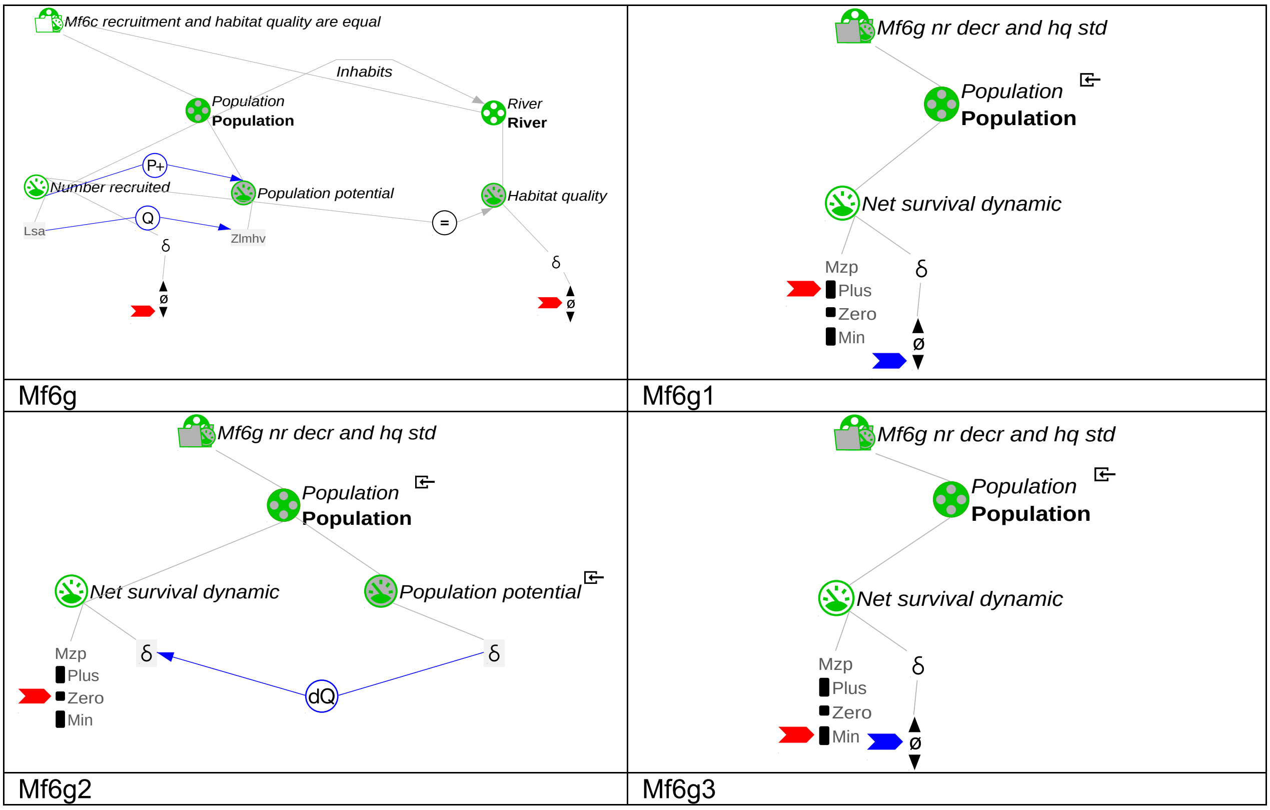

Figure A.6 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6g (*Number recruited* = *Habitat quality*) determines the *Population potential*.

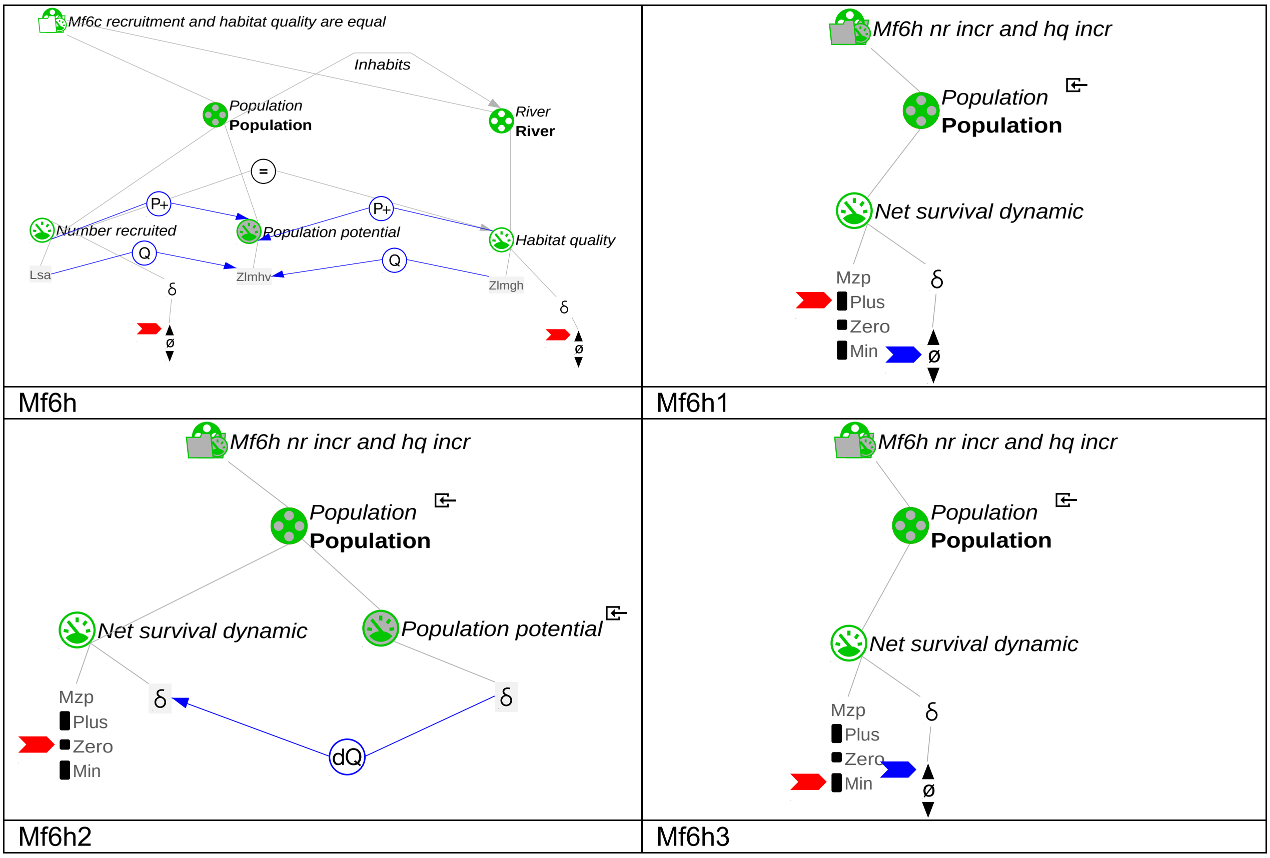

Figure A.7 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6h (*Number recruited = Habitat quality*) determines the *Population potential*.

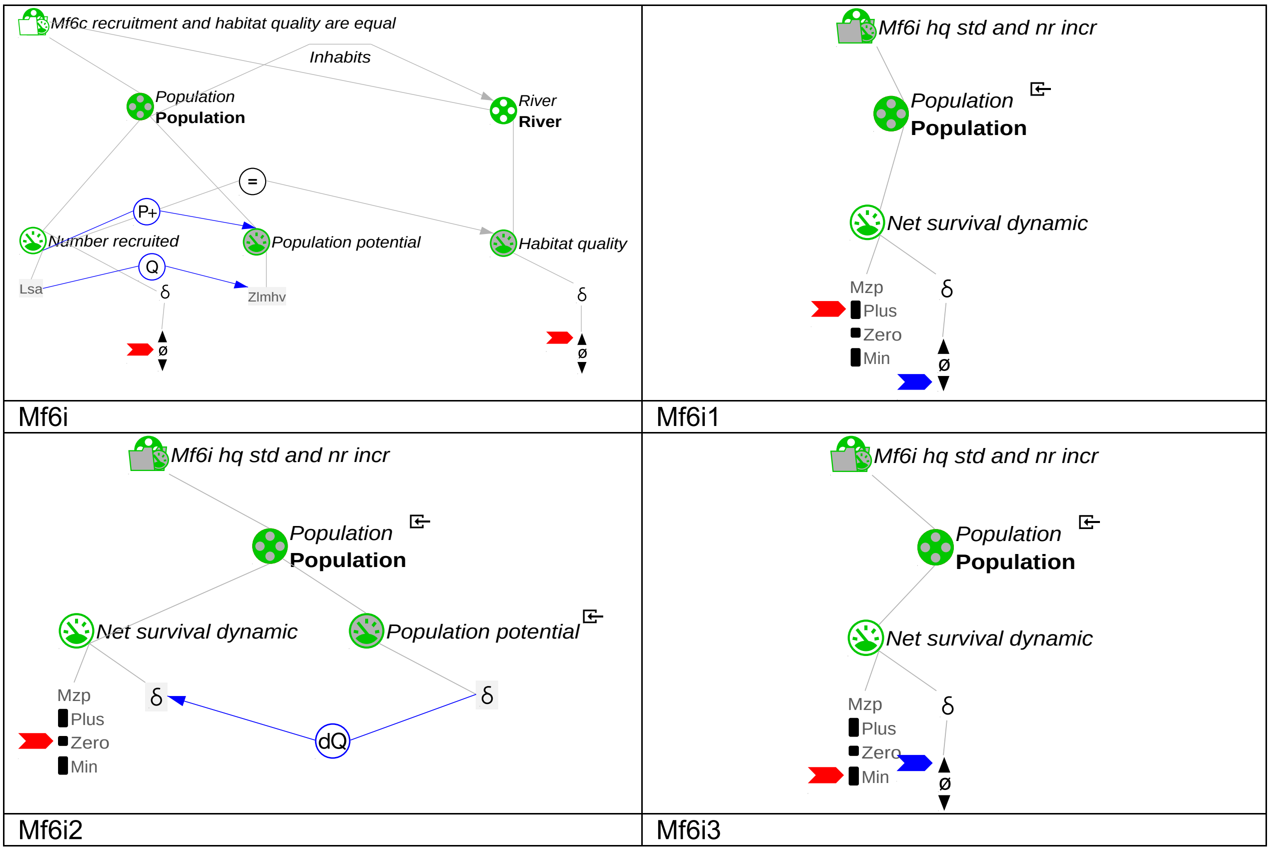

Figure A.8 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6i (*Number recruited = Habitat quality*) determines the *Population potential*.

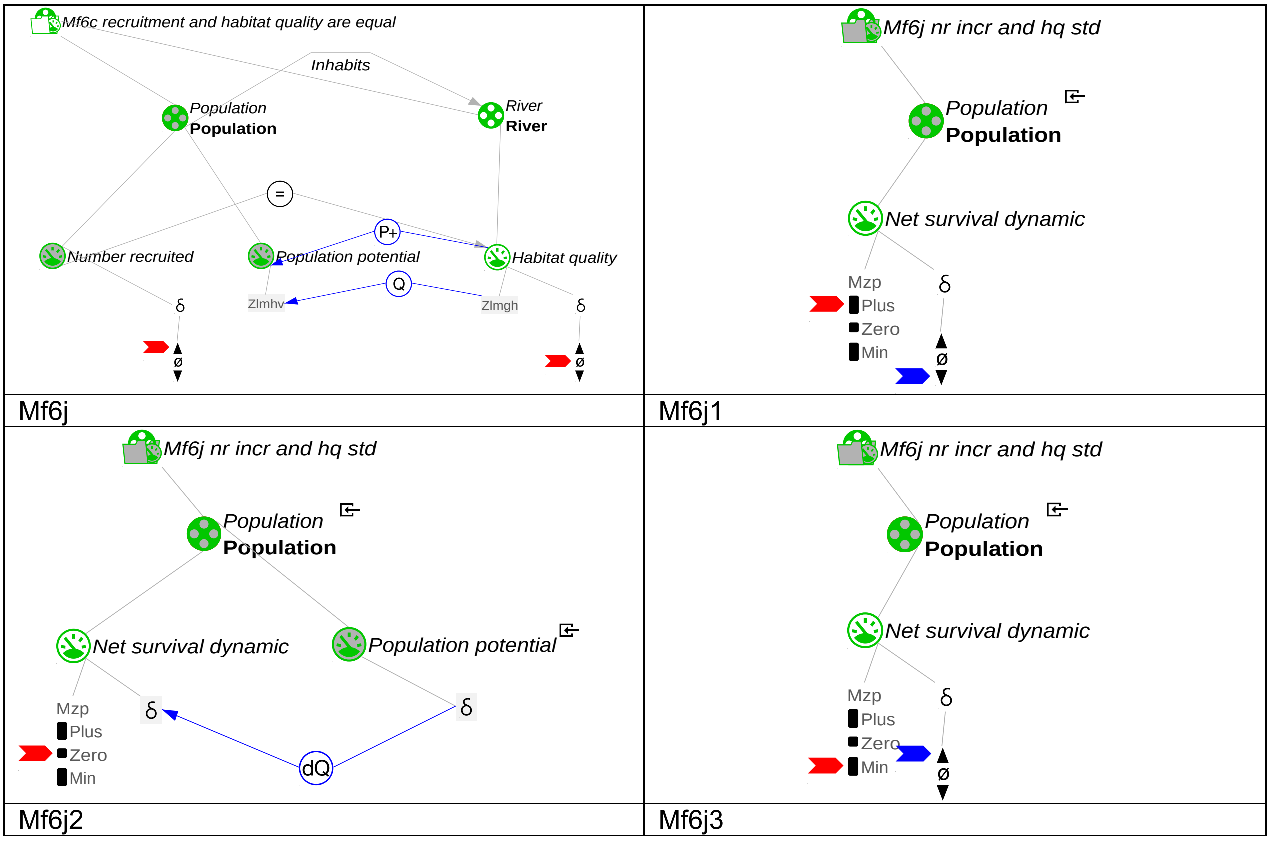

Figure A.9 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6j (*Number recruited = Habitat quality*) determines the *Population potential*.

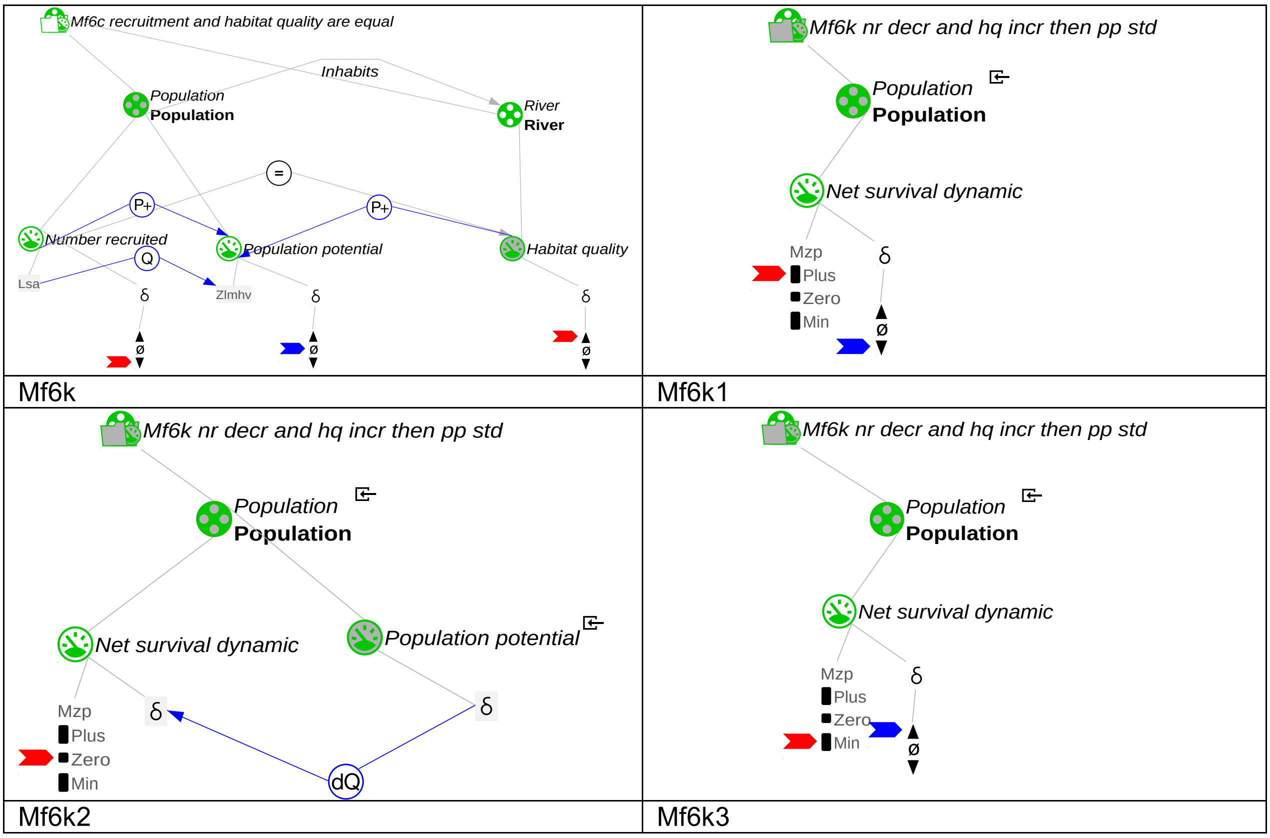

Figure A.10 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6k (*Number recruited = Habitat quality*) determines the *Population potential*.

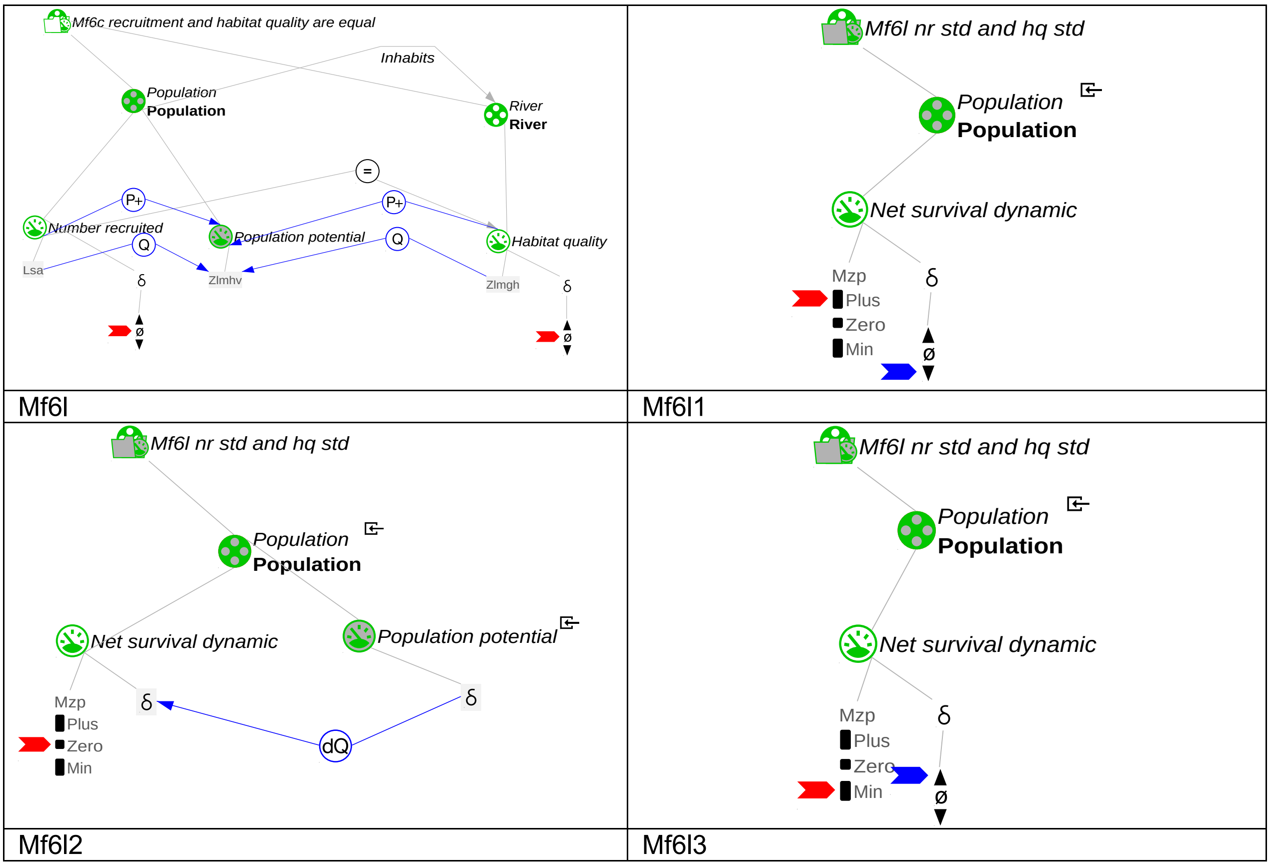

Figure A.11 Modelling solution for controlling the behaviour of *Net survival dynamic* in situations where Mf6l (*Number recruited = Habitat quality*) determines the *Population potential*.