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QR models and documentation for learning about sustainable development, focusing on basic biological, physical, and chemical processes related to the environment in the Riacho Fundo

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CO	Confidential, only for members of the consortium (including the Commission Services)	

<Final version>

Abstract

This document presents the final version of a complete qualitative simulation model of the Riacho Fundo case study to be used by stakeholders as learning material about sustainable development. The model explores aspects related to (a) the influence of urban drainage systems on soil conditions, economic activities and human well being; (b) the dynamics of water flow through the soil, springs and rivers, and its influence on economic activities in semi urbanized areas; and (c) the balance between erosion and soil protection measures for soil and river conditions, biodiversity and agricultural production. The document ends with a discussion about how the material can be used in educational contexts and the follow up of the present work.

Document history

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01	First draft	01/11/2006	Paulo Salles
02	Reviewed by Bert Bredeweg (UvA) and Tim Nuttle (UoJ)	15/01/2007	Paulo Salles
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Content

1 INTRODUCTION

This document describes an implemented qualitative simulation model about the Brazilian Riacho Fundo case study for the Project NaturNet – Redime. This case study bridges the gap between case studies with focus on problems of sustainability within water bodies (River Mesta, Bulgaria, and the Delta of the Danube River, Romania), and case studies that focus on restoration and rehabilitation of rivers (River Kamp, Austria, and Rivers Trent and Grand Ouse, England).

The Riacho Fundo basin has been one of the most disturbed areas under Brasilia's influence area since the beginning of the new capital construction, in the 1950s. It was progressively impacted by the transformation of natural areas into rural and urban areas. These changes eventually created a densely populated urban structure where few rural properties still keep an agricultural production of fruits and vegetables that supplies food processing industries. In these areas, springs, streams and natural vegetation patches are still protected and keep local biodiversity. Details of the physical and biological environment of the Riacho Fundo basin are summarized in Salles and Caldas (2006a).

In 2000, a group of stakeholders prepared a list of relevant problems in the Riacho Fundo basin (Salles and Caldas, 2006a). The uncontrolled land occupation and changes in land use was identified as the most important. Deforestation, biodiversity loss, problems related to water resources and management and low community participation in the decision making process were also considered highly relevant. Accordingly, the following objectives were set for this modelling effort:

(a) to improve understanding of environmental systems and problems that may affect sustainability in the basin;

(b) to demonstrate the effects of human actions, both positively and negatively influencing different aspects of the Riacho Fundo basin system;

(c) to mediate communication between stakeholders, policy makers, modellers and the public;

(d) to provide support for stakeholders to learn about sustainability.

With these problems and objectives in mind, three submodels were developed, addressing typical features of urban, semi-urban and rural areas of the Riacho Fundo basin: Urban drainage, Springs and Erosion, respectively.The prototype of these submodels was presented in Salles and Caldas (2006b). The present document reports the development of an integrated model that combines, within the the same library of scenarios and model fragments, the material produced for the three submodels. It is a large model that comprises, in its current stage of implementation, 24 entities, 11 processes and 45 quantities, organized in 65 model fragments, in order to produce 30 structurally different simulations (that is, similar scenarios with different initial values are not included).

During the implementation of this model we followed as much as possible the textual description presented in the deliverable D6.4.1 (Salles and Caldas, 2006a) and the guidelines set by Bredeweg et al. (2005). However, as the concepts became clearer and technical solutions were required in order to keep the simulations at a manageable size, new features were included into the models and some of the initial insights were left aside.

The relation between qualitative model components and concepts to be learned was pointed out in Salles and Bredeweg (1997). From this point of view, model fragments can be explored to represent self-contained conceptual units, that can be further combined with other model fragments to create models and simulations that represent conceptually more complex systems. Accordingly, concepts that should be learned by stakeholders are presented here in a contextualized way while the most relevant model components such as the entities and configurations, quantitites, processes, model fragments, scenarios and simulations are described.

Integration of this model with models produced in other case studies within the Naturnet Project is part of ongoing work, as well as the use of these models as didactic material to support stakeholders in learning about sustainable development. Of particular interest is the development of an integrated library of model fragments (Task 6.7: Integrated library of re-usable Qualitative Reasoning model fragments) currently developed by the University of Brasilia, and of curricula to address the contents of the models (Task 6.8: Guidelines of Sustainable Development curriculum and content), under responsibility of the University of Jena partner.

This Deliverable is organized as follows: in section 2, the entities, configurations and quantities used in the Riacho Fundo model are presented. Next, the submodels are described in details: the submodels Urban drainage, Springs and Erosion are presented, respectively, in sections 3, 4 and 5. Ongoing work to further improve and expand the integration of these submodels is briefly commented in section 6. Finally, in section 7, a discussion and the conclusions about the whole modelling effort are presented.

2 Entities, configurations and quantities

The Riacho Fundo model consists of three submodels presented in the milestone 'M6.4 First prototype of a running simulation model of the Riacho Fundo case study' (Salles and Caldas, 2006b). These submodels address problems related to the drainage system in urban areas, water infiltration and springs in semi-urban areas and erosion in rural areas of the basin. Accordingly, entities and the selected quantities reflect the goals set for each submodel. Initially, the Entity hierarchy for the integrated model is presented; next, screenshots of the modelling workbench, Garp3, are used to illustrate how configurations are used to relate the entities; finally the quantities and respective quantity spaces are summarized.

2.1 Entities

The Entity hierarchy for the integrated model is presented in the following figure:

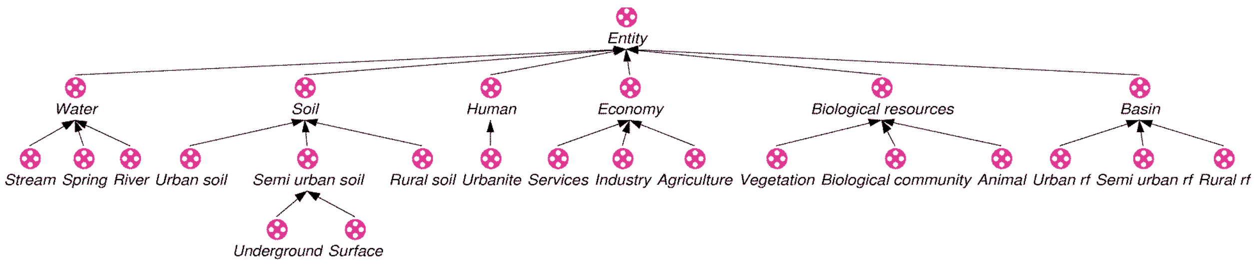
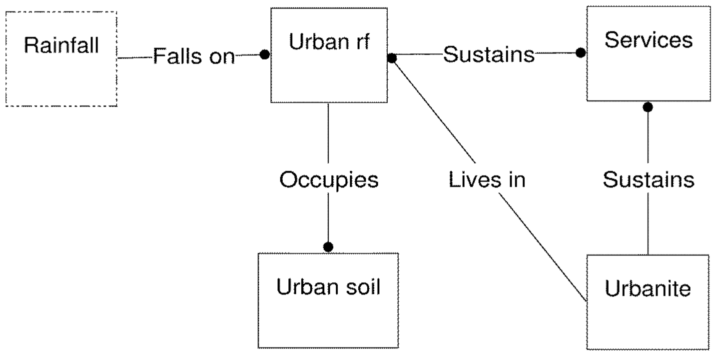


Figure G.01. Entity hierarchy for the integrated Riacho Fundo model.

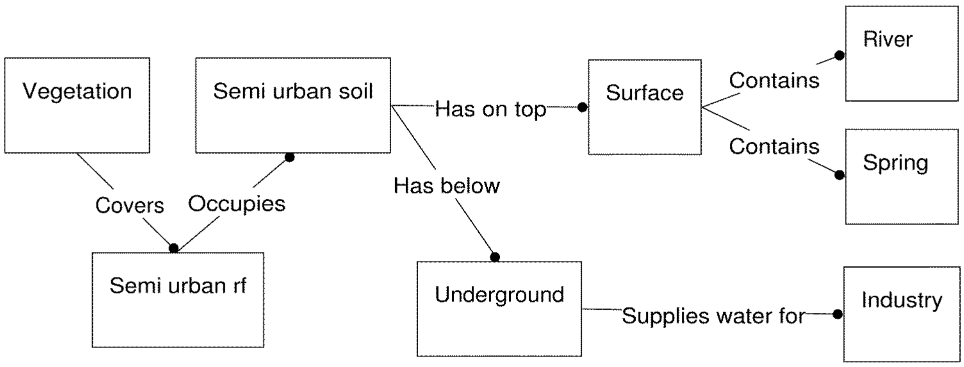
The entities are defined according to the three main perspectives from which the Riacho Fundo basin will be described: urban areas ('Urban rf'), semi-urbanized areas ('Semi urban rf') and rural areas ('Rural rf'). These entities characterize the structure of the system being modelled in each submodel. Accordingly, they represent the main types of land use, identified by three types of soil: 'Urban soil', 'Semi-urban soil' (with subtypes 'Underground' and 'Surface') and 'Rural soil'. In these areas economic activities are represented by the entities 'Services', 'Industry' and 'Agriculture', respectively. The other entities represent relevant types of biological resources and of water bodies found in the Riacho Fundo basin, and one particular type of human being, the urbanites that live in the basin.

2.2 Configurations

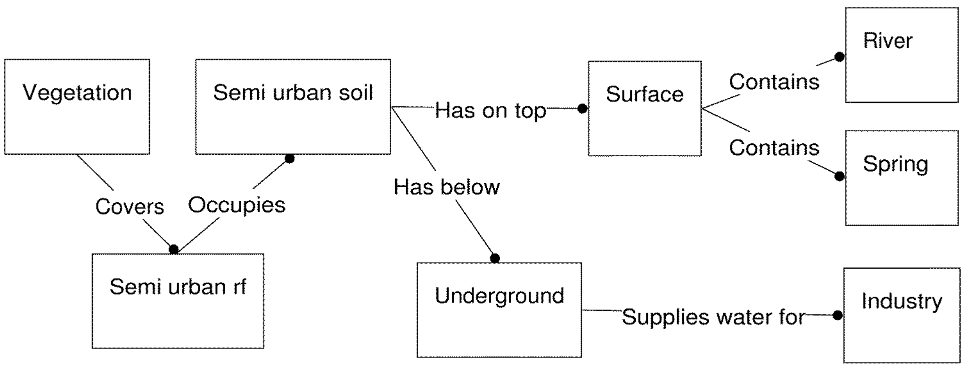
The above mentioned entities are related among themselves by means of *configurations*. Entities and configurations create the structure of the system being modelled. The figures below show the full structure of the three submodels that compose the Riacho Fundo model:



(a) Urban drainage submodel



(b) Springs submodel



(c) Erosion submodel

Figure G.02 Entities and configurations used to define the system structure in submodels of the Riacho Fundo model: (a) Urban drainage; (b) Springs; (c) Erosion.

2.3 Quantities and Quantity spaces

The quantities used in the Riacho Fundo model and their respective sets of possible qualitative values (the quantity spaces) are presented in the following three tables. In these tables, rates of processes are presented before the other quantities. The quantity spaces are identified by labels that read as follows: mzp = {*minus*, *zero*, *plus*}; zp = {*zero*, *plus*}; zsml = {*zero*, *small*, *medium*, *large*}; and sml = {*small*, *medium*, *large*}.

Table1: Urban drainage submodel

Quantity	Quantity Space	Remarks
Rates of processes		
Build up rate	mzp	Rate of changes in the soil, including both soil creation (recovery) and destruction (erosion)
Improvement rate	mzp	Rate of the aggregate of processes that determine human well being; it is calculated in abstract terms from the balance between positive and negative factors
Uncontrolled flow	mzp	Rate of the water flow in storm events, calculated as the balance between water runoff and the amount of water adequately drained by natural or human made ways
Other quantities		
Drained water	zsml	Refers to water that is drained in a controlled way, either by natural or engineered systems
Economic damage	zsml	Refers to damage caused by garbage, mud, biological contaminants and objects transported by the water runoff
Eroded soil	sml	Refers to the area damaged by erosion
Flooded area	zsml	Area that accumulates water in storm events, mostly because the soil is impermeable and the drainage system is not adequate
Negative factors	zsml	Refers to all the negative influences on human well being (diseases, economic losses)
Positive factors	zsml	Refers to all the positive influences on human well being (health, education, safety and clean environment)
Rain	zsml	Precipitation on the basin area
Transported garbage	zsml	Refers to all the materials carried by the water runoff in a storm event. In the Riacho Fundo, it includes debris from the vegetation, mud and human artifacts
Uncontrolled water	zsml	Amount of water that runs without adequate control and that is potentially dangerous or damaging
Water runoff	zsml	Total amount of water that results from the rainfall and does not infiltrate in the soil within a short period
Well being	zsml	Feeling of being healthy, happy, confortable, having satisfied the basic needs (education, housing, spiritual, environmental and economical aspects)

Table G.01. Quantities and quantity spaces used in the Urban drainage submodel.

Table 2: Springs submodel

Quantity	Quantity Space	Remarks
Rates of processes		
Industrial production rate	mzp	Refers to a number of processes related to different types of industrial production; in the Riacho Fundo they are mostly related to food processing and the manufacture of agricultural products
Infiltration rate	zp	Related to water flow process, this rate refers to the speed of transportation of water from the surface to the underground. In this model it is associated to the level of aggregation of soil particles, to the amount of water at the surface and at the underground
Particle aggregation rate	mzp	Refers to processes that make the soil particles more aggregated or disaggregated under opposite pressures from urbanization and biological activities of plants, animals and microrganisms
Vegetation growth	mzp	Refers to changes in the biomass of the vegetation due to somatic growth and to the basic population processes (natality, mortality, migration)
Other quantities		
Amount of water	zsml	Quantity of liquid water found in different locations in the basin (underground, surface, springs, streams, rivers)
Biological pressure	zsml	Refers to the pressure for the disaggregation of the soil resulting from all biological activity (of plants, fungi, earthworms and other animals)
Industrial products	zsml	In the Riacho Fundo basin, includes mostly industrialized food or other agroindustrial products
Level of aggregation	zsml	Proximity between the particles in the soil. It is influenced by the forces of urbanization (that causes the soil to become more compact) and biological activities (that reduce the level of aggregation)
Resource consumption	zsml	Amount of materials consumed during the industrial production. In the Riacho Fundo, it is limited by a number of factors (human, financial, and technological resources)
Resource inflow	zsml	Amount of resources used as input for industrial activitives. In Riacho Fundo it depends very much on water, soil fertility and agricultural raw materials
Regeneration	zsml	Refers to the amount of vegetation regenerated by natural or human-induced processes. It may include somatic growth and population growth
Degradation	zsml	Refers to the amount of vegetation destroyed by natural and human related actions (senescence, burning, mortality)

Table G.02. Quantities and quantity spaces used in the Springs (semi-urban) submodel.

Table 3: Erosion submodel

Quantity	Quantity Space	Remarks
Rates of processes		
Agricultural production rate	mzp	Rate of the aggregate of processes related to food and material production in agriculture
Erosion rate	zp	Rate of the process that destroy the soil caused by rain, water runoff and wind
Restoration rate	zp	Rate of the aggregate of (natural and human-induced) processes that lead to soil creation
Vegetation growth	mzp	Refers to changes (increase and decrease) in the biomass of the vegetation due to basic population processes (natality, mortality, migration) and to somatic growth
Other quantities		
Agricultural products	zsml	Amount of food and raw agricultural materials produced in the basin
Amount of water	zsml	Quantity of liquid water found in different locations in the basin (underground, surface, springs, streams, rivers)
Biodiversity	zsml	Population, species and community diversity of vertebrates (mammals) found in the Riacho Fundo basin
Degradation	zsml	Refers to the amount of destroyed vegetation due to natural (senescence, mortality) and human provoked (deforestation, burning) processes
Fertility	zsml	Refers to the ability of the soil to produce good crops, given the concentration of nutrients and organic matter
Nutrient	zsml	Concentration of nutrients in the soil. In this model, it is reduced by laminar erosion
Regeneration	zsml	Amount of vegetation that grows due to regular reproduction, immigration of propagules, seed bank and somatic growth
Removed soil	zsml	Amount of soil that is displaced due to erosion and then transported often to water bodies
Resource consumption	zsml	Amount of materials required for the agricultural production. In the Riacho Fundo, it is limited by a number of factors (human, financial, and technological resources), beside soil fertility
Resource inflow	zsml	Amount of resources used as input for agricultural activitives. In the Riacho Fundo it depends very much on soil quality, seeds, water and energy
Stream depth	zsml	Refers to the water depth, which is reduced due to the deposit of sediments
Sediment	zsml	Refers to the layer of solid substances (soil) carried to the water body by erosion processes that settle at the bottom of the river
Vegetation cover	zsml	Amount of vegetation distributed over the Riacho Fundo land
Vertebrate survival	zsml	Refers to the number of animals (mammals) that survive under certain environmental conditions

Table G.03. Quantities and quantity spaces used in the Erosion (rural) submodel.

3 Submodel Urban Drainage

The Urban Drainage (UD) submodel explores the use of assumptions to provide two perspectives to the water flow control in storm events within the Riacho Fundo basin: (a) without any control on the water runoff; and (b) with an increasing use of an engineered drainage system, reducing this way the uncontrolled water flow. Comparisons between simulations under these assumptions provide better means for understanding the influence of the urban drainage system on the urban environment, the economy and human well being.

Using the simulations supported by this model, it should be possible to answer the following question: *what are the benefits of having a good infrastructure for the drainage of rain water in the urban area of Riacho Fundo with respect to soil protection, economic damages caused by garbage, and the human well being?*

3.1 Model fragments

The UD submodel consists of 21 model fragments, being 17 static, three process and one agent. These model fragments are presented below.

3.1.1 Water in urban area

The basic structure of water control in urban Riacho Fundo is presented in the static model fragment 'Water in urban area'. It introduces the entity 'Urban rf' and three quantities: *Drained water*, *Water runoff* and *Uncontrolled water*:

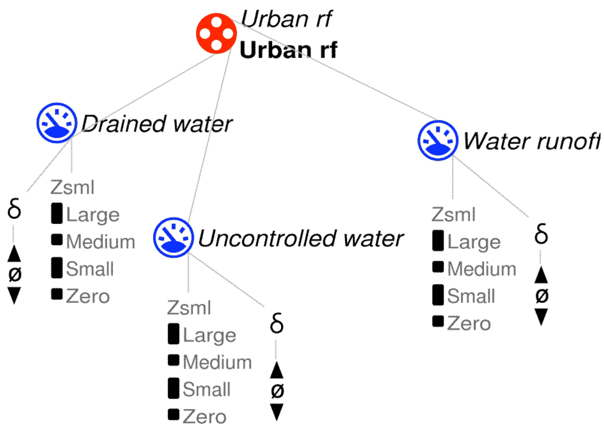


Figure UD.01. Static model fragment 'Water in urban area'.

3.1.2 Assume drainage zero and steady

The two perspectives for approaching the drainage system are implemented by means of the assumptions 'Drainage zero steady' and 'Drainage increasing'. The static model fragment 'Assume drainage constant zero and steady' implements the former:

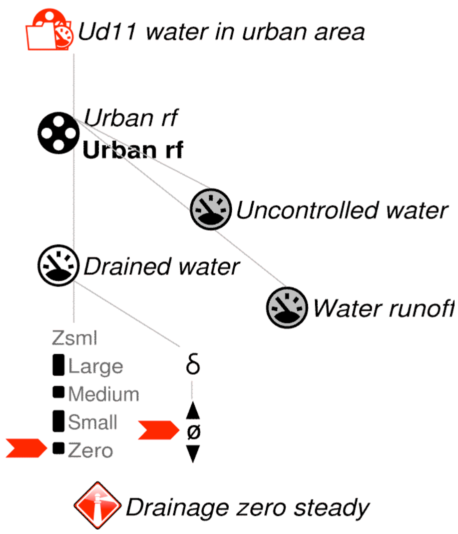


Figure UD.02. Static model fragment 'Assume drainage zero and steady'.

3.1.3 Assume drainage increasing

The assumption 'Drainage increasing' is implemented in the static model fragment 'Assume drainage constant increasing':

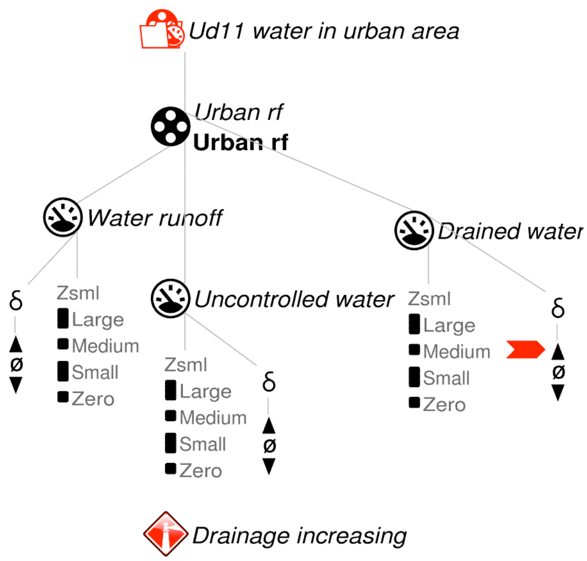


Figure UD.03. Model fragment 'Assume drainage increasing'

3.1.4 Controlled drainage process

The process model fragment ‘Controlled drainage process’ introduces the rate *Uncrontrolled flow* and describes the mechanism that operates in the drainage system:

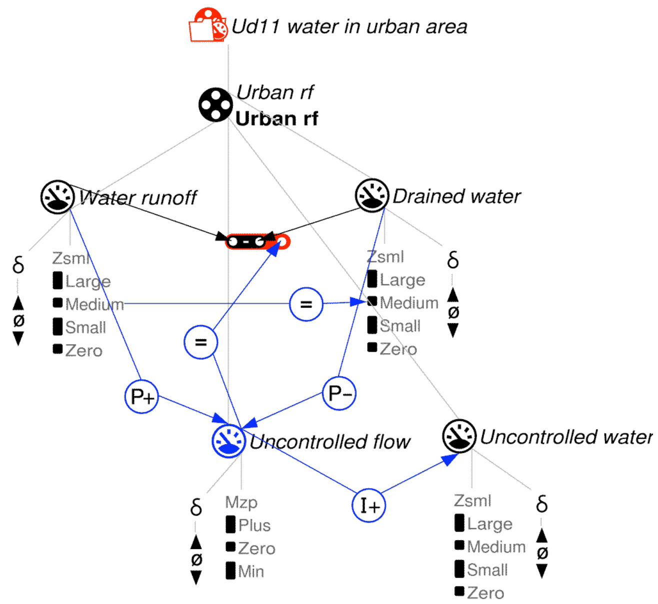


Figure UD.04. Model fragment ‘Controlled drainage process’.

Three additional model fragments were included in the library as children of this model fragment. They don’t affect the behaviour of the system as they only have, as conditions, (in)equalities stating that *Water runoff* is equal, greater than and smaller than *Drained water*, in order to support inequality reasoning in Garp3.

3.1.5 Rainfall

The water runoff is produced by the rainfall, a climate factor modelled as an external factor. This agent model fragment introduces the agent ‘Rainfall’ and the quantity *Rain*, and shows how it influences and sets the value of *Water runoff*:

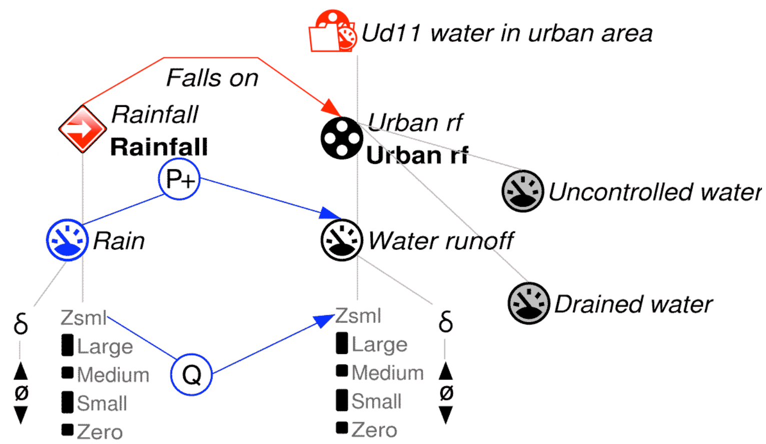


Figure UD.05. Agent model fragment ‘Rainfall’.

3.1.6 Flooded area

An important effect of uncontrolled flow of water is the creation of flooded areas in the urban areas. This is captured in the static model fragment 'Flooded area'. It is assumed that the size of the flooded areas corresponds to the quantity of *Uncontrolled water*:

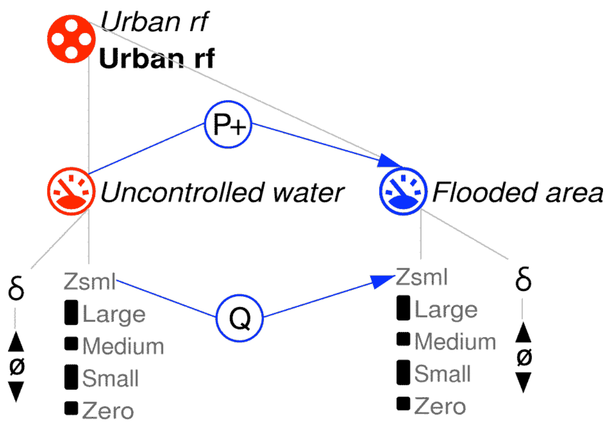


Figure UD.06. Static model fragment 'Flooded area'.

3.1.7 Eroded soil affects build up rate

The notion of soil protection in urban areas, an aggregated process that 'creates' soil and reduces the area of eroded soil, is captured in two model fragments: 'Eroded soil affects build up rate' and 'Soil buil up process'. The former introduces the entity 'Urban soil' and relates the quantities *Eroded soil* and *Build up rate*:

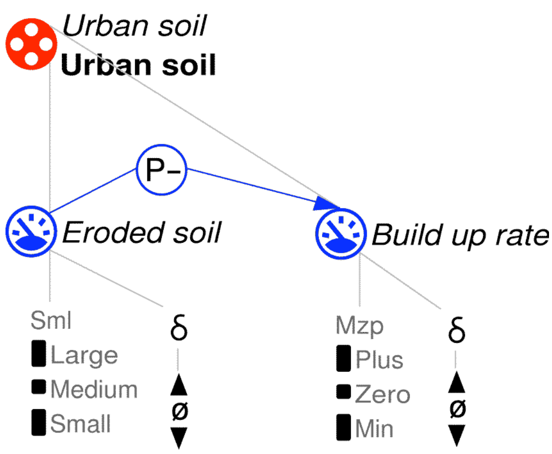


Figure UD.07. Static model fragment 'Eroded soil affects build up rate'.

3.1.8 Soil build up process

The process of creating soil is represented in the model fragment ‘Soil build up process’. This process is meant to represent natural and human-induced activities that protect the existing soil and recover the eroded soil. Note the feedback loop to represent the notion that when the eroded area is increasing, the soil build up rate will be decreasing.

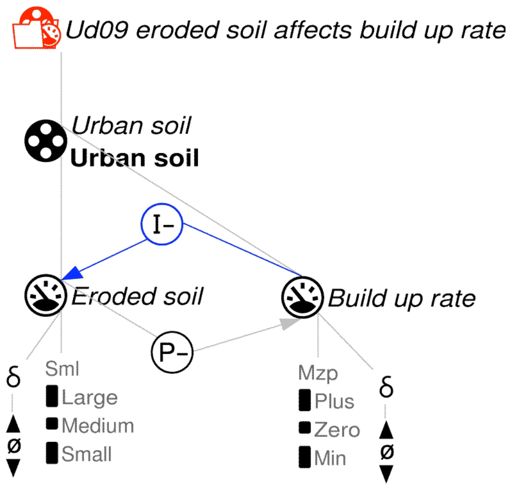


Figure UD.08. Process model fragment ‘Soil build up process’.

3.1.9 Uncontrolled water and soil

The effects of the uncontrolled water flow on soil protection are presented in this model fragment. Note that instead of representing the erosion process itself (represented in the submodel Erosion), increasing uncontrolled water affects the quantity *Build up rate* and may lead it to assume the value *Minus*. A negative build up rate can be seen as equivalent to the erosion process and destroys the urban soil.

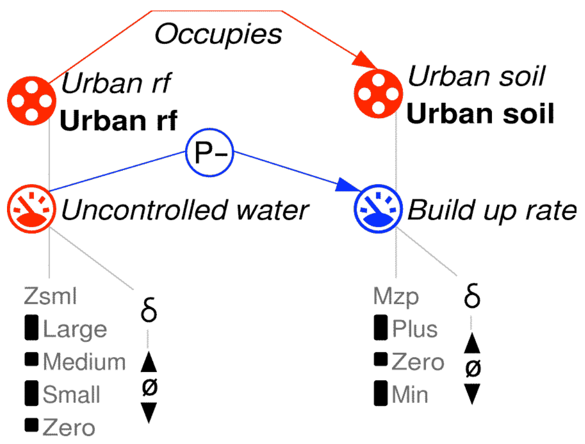


Figure UD.09. Static model fragment ‘Uncontrolled water and soil’.

3.1.10 Garbage causes damage

When garbage and vegetation debris are transported throughout the city by the uncontrolled flow of water, it may spread diseases and cause damage to buildings and economic activities. In Riacho Fundo events related to storms affect the commerce and a large number of garages and vehicle repair shops, represented in the model by the entity 'Services'. These concepts are captured in two model fragments, 'Garbage causes damage' and 'Economic damage', shown in the following figures:

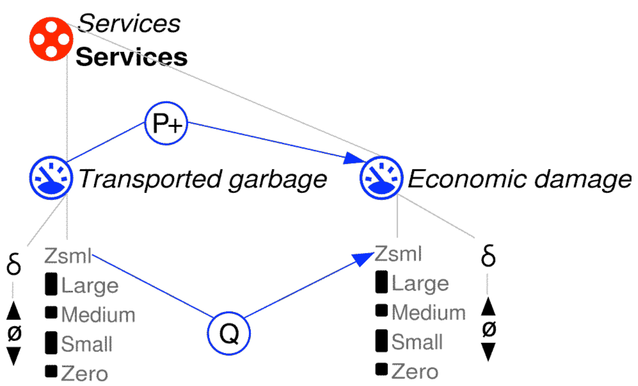


Figure UD.10. Static model fragment 'Garbage causes economic damage'.

3.1.11 Water and transported garbage

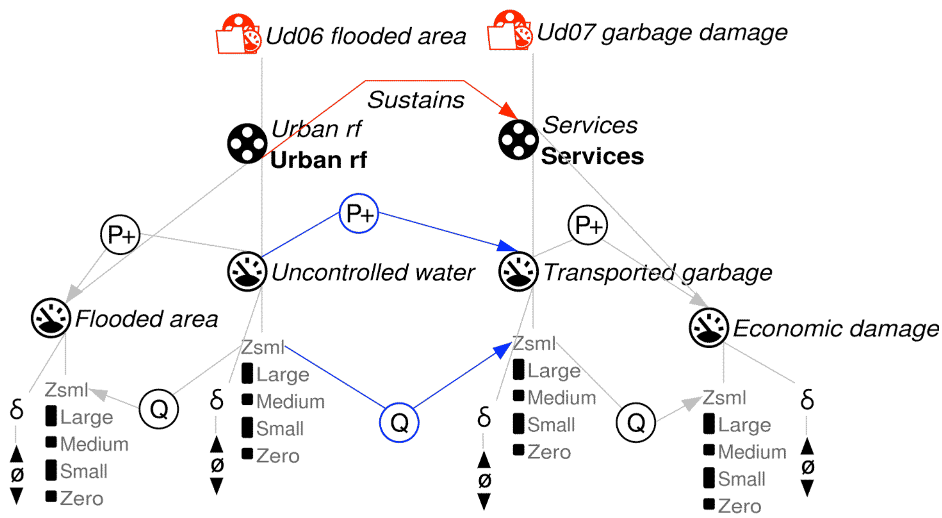


Figure UD.11. Static model fragment 'Water transports garbage'.

3.1.12 Human well being

Lack of a drainage system in urban areas eventually affects human well being. In this submodel, the notion of well being is related to collections of positive and negative factors that are computed in order to define whether or not the well being is improving. Four model fragments are used to implement these concepts: 'Human well being', 'Drainage and well being', 'Assume positive factors on well being constant and *small*' and 'Well being improvement process'. The static model fragment 'Human well being' introduces the entity 'Urbanite' and three quantities: *Positive factors*, *Negative factors* and *Well being*:

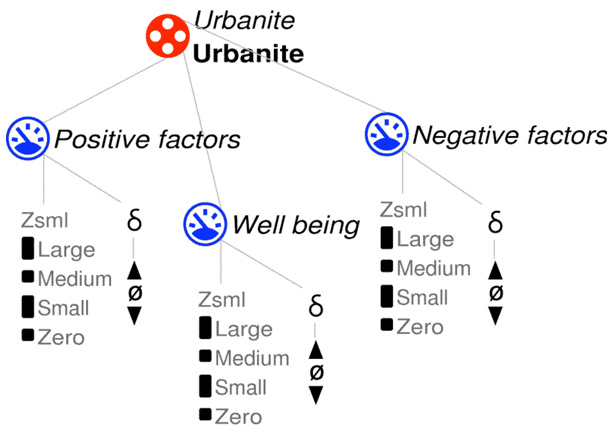


Figure UD.12. Static model fragment 'Human well being'.

3.1.13 Drainage and well being

This static model fragment shows the causal chain that influences *Negative factors*:

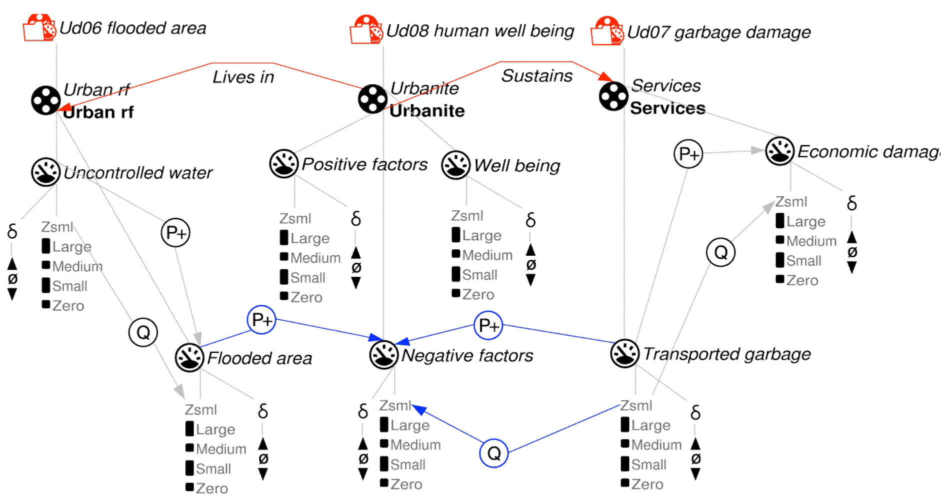


Figure UD.13. Static model fragment 'Drainage and well being'.

3.1.14 Assume positive factors on well being constant and small

By keeping constant the values of magnitude and derivative of positive factors, only changes in the negative factors are used to explain the dynamics of the system. This assumption is implemented in this static model fragment:

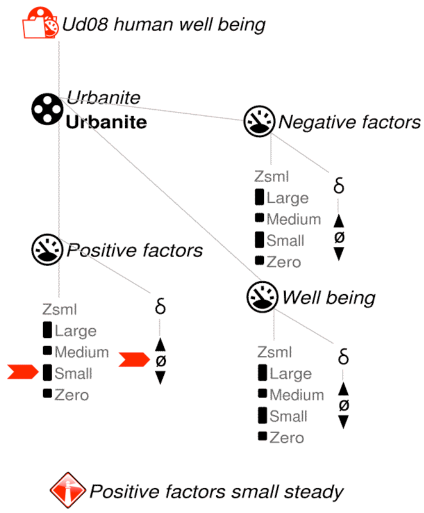


Figure UD.14. Static model fragment 'Assume positive factors on well being constant and *small*'.

3.1.15 Well being improvement process

Improvement on human well being is described as a mechanism that takes into account the positive and negative factors. The rate of improvement is calculated from the difference between these factors, as shown in this process model fragment. Given the assumption presented in the previous model fragment (section 3.1.14), when *Negative factors* is greater than *Small*, the quantity *Improvement rate* may become negative and cause *Well being* to decrease. As in the 'Controlled drainage process' situation (section 3.1.4), three children model fragments were added to the library with inequalities between *Positive* and *Negative factors* to support inequality reasoning in Garp3.

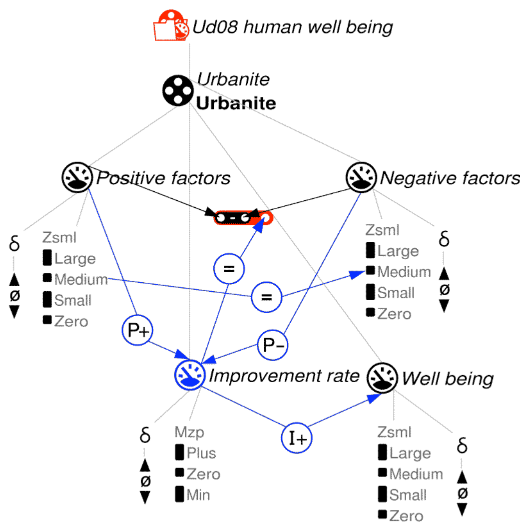


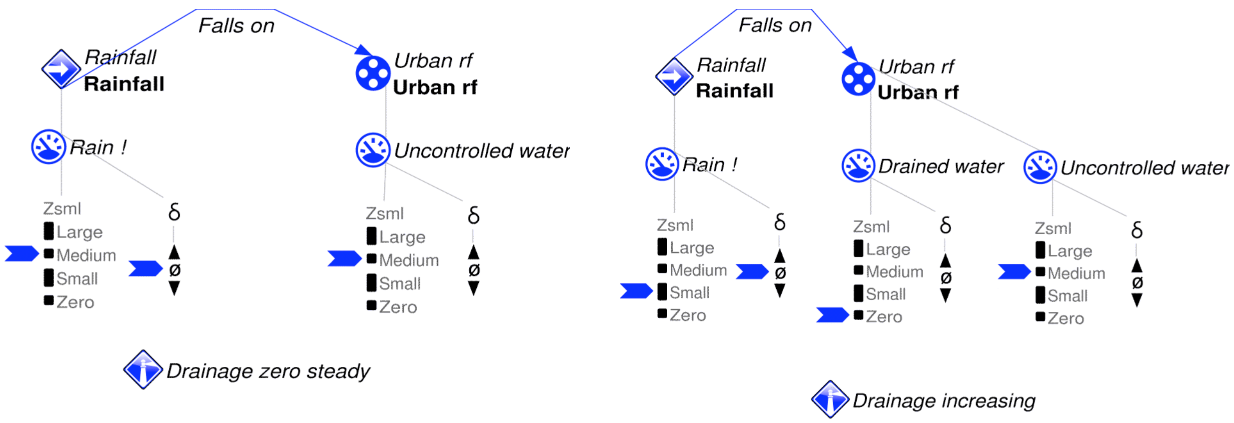
Figure UD.15. Model fragment 'Well being improvement' process.

3.2 Scenarios

Currently this submodel has 10 scenarios, being half with the assumption 'Drainage zero steady' and half with the assumption 'Drainage increasing'. This way, the results can be compared, providing more insights on the importance of urban drainage systems. The first eight will be described as a summary, and the last two with more details. In order to simplify all the simulations presented here, it is assumed that *Rain* and *Water runoff* are constant. Note that in all the scenarios the quantity *Rain* is followed by an exclamation mark, that indicates the exogenously driven behaviour, in this case, the magnitude being constant. *Water runoff* is also constant due to the correspondence implemented in the model fragment shown in section 3.1.5. Finally, for better understanding the simulations, it may be useful to consult the causal model of the Urban drainage submodel, presented in section 3.2.5 (Figure UD.22).

3.2.1 Drainage zero constant and increasing

The simplest scenarios deal with six quantities: *Uncontrolled flow*, *Uncontrolled water*, *Flooded area*, *Drained water* and the two constants. The scenarios 'Drainage zero constant' and 'Drainage increasing' are presented below:



(a) (b)

Figure UD.16. Initial scenarios (a) Drainage zero constant'; and (b) 'Drainage increasing'.

Scenario name	'Drainage zero constant'
Full simulation	5 states
Initial states	[1, 2, 3]
End states	[2, 4, 5]
Relevant behaviour path	[1→ 5] and [2→4]
Behaviour description	Given the initial conditions, *Uncontrolled water* may increase to *Large* in state [5] or decrease to *Small* in state [4]. The quantity *Flooded area* follows the same behaviour.

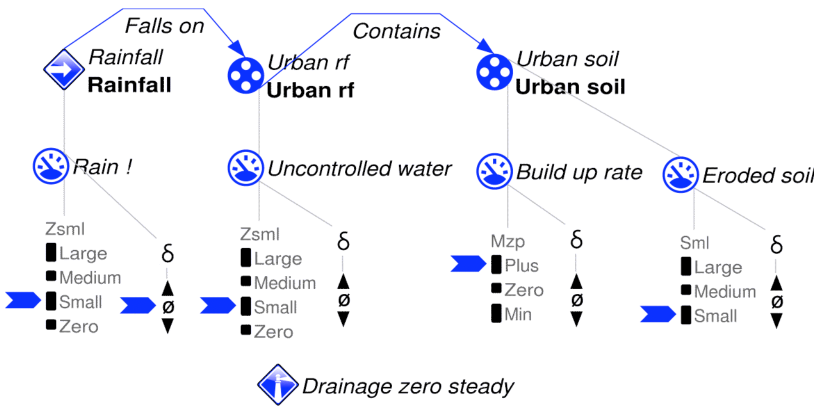
Table UD.01. Simulation summary: scenario 'Drainage zero constant'

Scenario name	‘Drainage increasing’
Full simulation	12 states
Initial states	[1]
End states	[10]
Relevant behaviour path	[1→2→3→4→7→8→12→10]
Behaviour description	Due to the behaviour of *Uncontrolled water*, *Flooded area* increases in states 1 and 2, become stable in 3 and decrease in the rest of the simulation. *Drained water* is increasing in all the states, and reaches the interval *Large* in state 8.

Table UD.02. Simulation summary: scenario ‘Drainage increasing’

3.2.2 Drainage (zero and increasing) and soil

In this pair of simulations, the quantities *Build up rate* and *Eroded soil* are included to the previous ones.



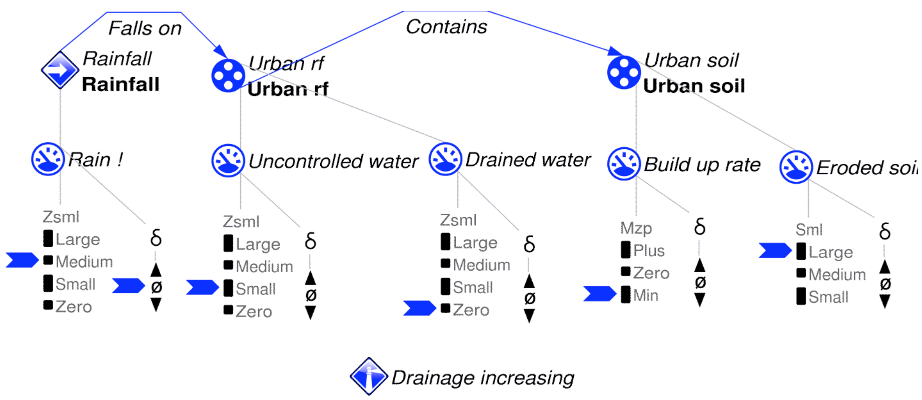


Figure UD.17. Initial scenarios (a) ‘Drainage zero and soil’; and (b) ‘Drainage increasing and soil’.

Scenario name	'Drainage zero and soil'
Full simulation	23 states
Initial states	[1, 2, 3, 4, 5]
End states	[4, 5, 15, 22]
Relevant behaviour path	[1→9→12→17→22]
Behaviour description	*Uncontrolled water* and *Flooded area* increase during the whole simulation. Initially *Eroded soil* decreases, becomes stable in state 9 and increases during the rest of the simulation. At the end these quantities have value *Large*.

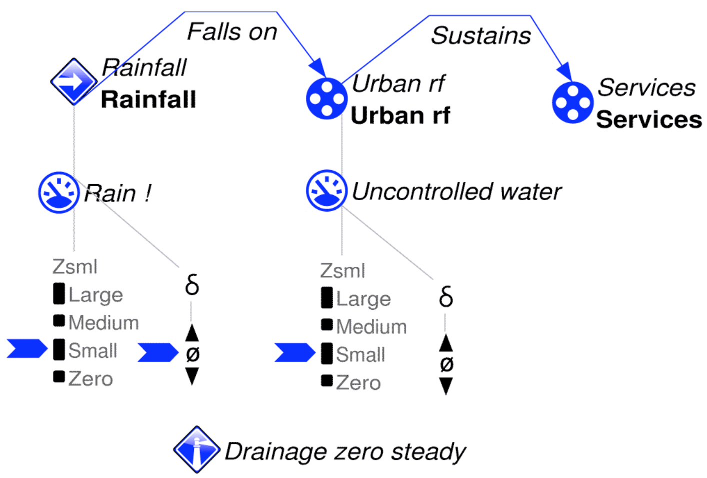
Table UD.03. Simulation summary: scenario 'Drainage zero and soil'.

Scenario name	'Drainage increasing and soil'
Full simulation	19 states
Initial states	[1]
End states	[7, 8, 19]
Relevant behaviour path	[1→2→3→10→11→15→16→18→19]
Behaviour description	Initially *Uncontrolled water* and *Flooded area* increase, then become stable in state 3 and decrease in the rest of the simulation. *Eroded soil* is increasing, then becomes stable in state 15 and decreases and reaches the value *Small* in state 19.

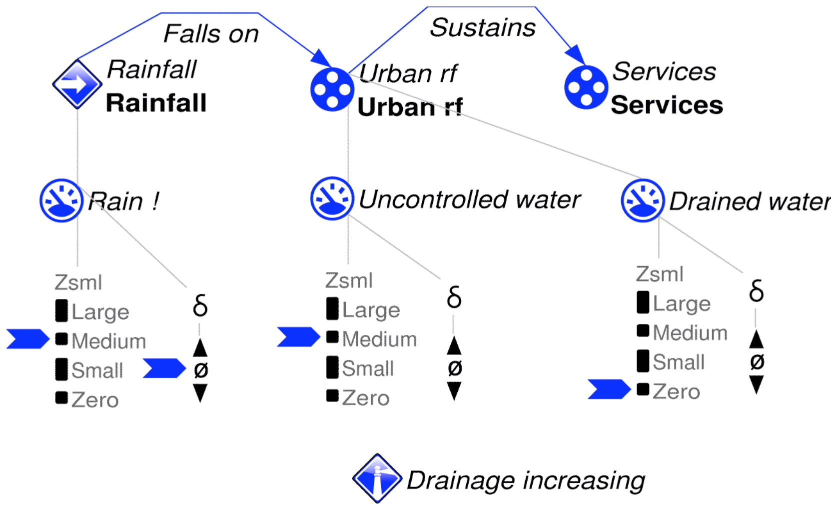
Table UD.04. Simulation summary: scenario 'Drainage increasing and soil'.

3.2.3 Drainage (zero / increasing) and economy

In this pair of simulations, the quantities *Transported garbage* and *Economic damage* are included, but *Build up rate* and *Eroded soil* are not.



(a)



(b)

Figure UD.18. Initial scenarios (a) 'Drainage zero and soil'; and (b) 'Drainage increasing and soil'.

Scenario name	'Drainage zero and economy'
Full simulation	5 states
Initial states	[1, 2, 3]
End states	[2, 3, 5]
Relevant behaviour path	[1→4→5]
Behaviour description	*Uncontrolled water*, *Flooded area*, *Transported garbage* and *Economic damage* increase during the whole simulation.

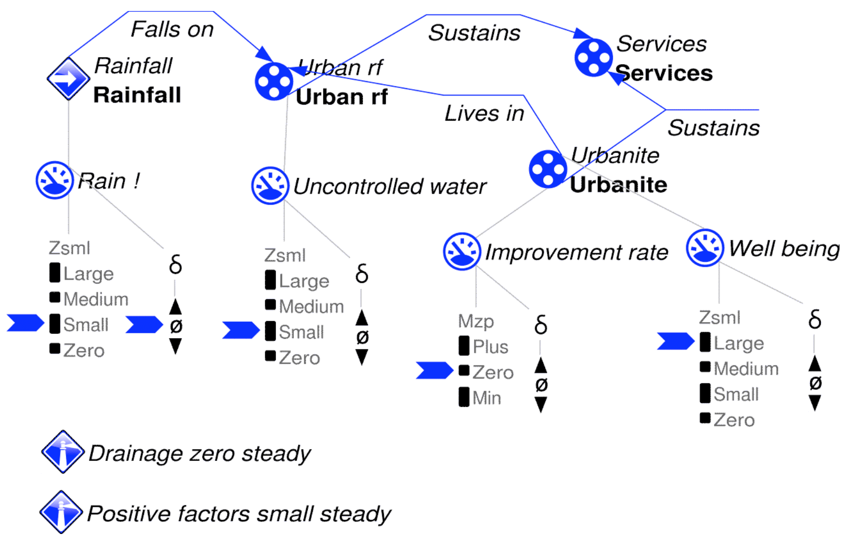
Table UD.05. Simulation summary: scenario 'Drainage zero and economy'.

Scenario name	'Drainage increasing and economy'
Full simulation	6 states
Initial states	[1]
End states	[6]
Relevant behaviour path	[1→2→3→4→5→6]
Behaviour description	Initially *Uncontrolled water*, *Flooded area*, *Transported garbage* and *Economic damage* increase, then become stable in state 3 and decrease in the rest of the simulation. *Drained water* steadily increases and reaches the interval *Large* in state 4.

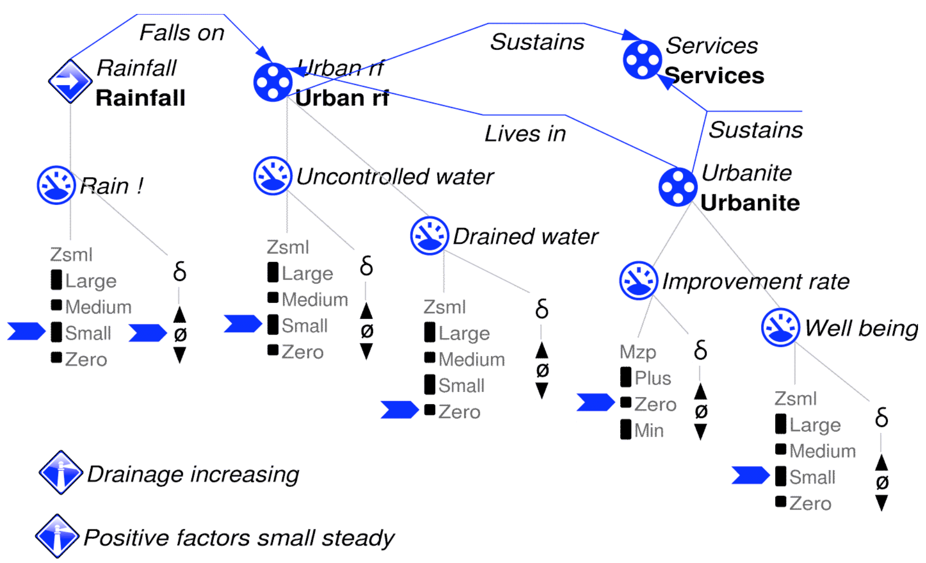
Table UD.06. Simulation summary: scenario 'Drainage increasing and economy'.

3.2.4 Drainage (zero / increasing), economy and well being

In this pair of simulations, 12 quantities are involved. Beside *Transported garbage* and *Economic damage*, the quantities *Positive factors*, *Negative factors*, *Improvement rate* and *Well being* are now included.



(a)



(b)

Figure UD.19. Initial scenarios (a) 'Drainage zero, economy and well being'; and (b) 'Drainage increasing, economy and well being'.

Scenario name	‘Drainage zero, economy and well being’
Full simulation	13 states
Initial states	[1, 2, 3]
End states	[2, 4, 11]
Relevant behaviour path	[1→5→7→10→12→11]
Behaviour description	*Uncontrolled water*, *Flooded area*, *Transported garbage* and *Economic damage* increase during the whole simulation. *Negative factors* follows the same beahviour. *Well being* starts stable, then decreases within the interval *large* until state 10 and reaches the value *Small* in state 11.

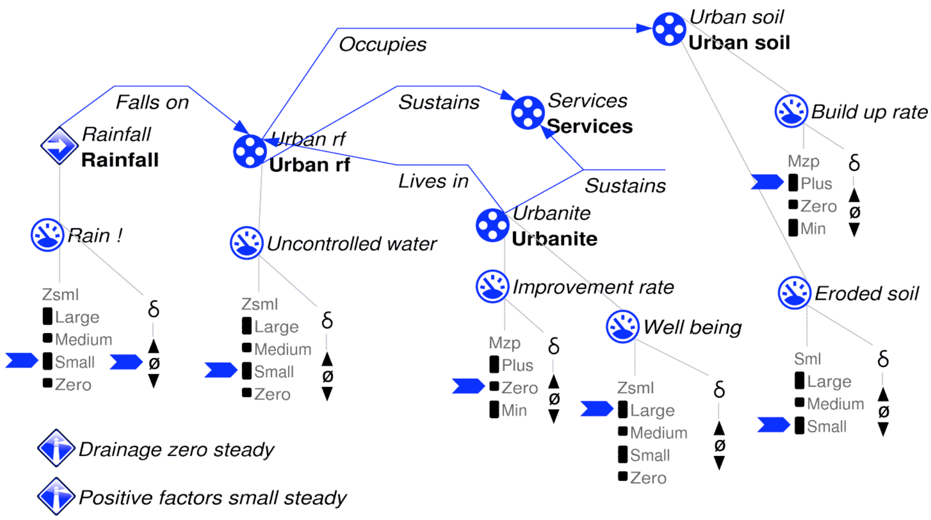
Table UD.07. Simulation summary: scenario ‘Drainage zero, economy and well being’.

Scenario name	‘Drainage increasing, economy and well being’
Full simulation	33 states
Initial states	[1]
End states	[30]
Relevant behaviour path	[1→2→3→8→9→20→21→31→32→19→24→17→25→30]
Behaviour description	This simulation produces a number of possible behaviour paths, particularly if *Drained water* takes much time to change to the value *Medium*. In the selected behaviour path, it happens in state 21 and in the next state it goes to *Large*. *Uncontrolled water* increases in the beginning and becomes stable in state 9; then starts decreasing, reaches the value *Small* in state 19 and does not go to *Zero*. *Flooded area*, *Transported garbage, Economic damage* and *Negative factors* exhibit the same behaviour. *Well being* starts stable, then decreases within the interval *Small*. In state 24 it becomes stable again, starts increasing and reaches the value *Large* in state 30.

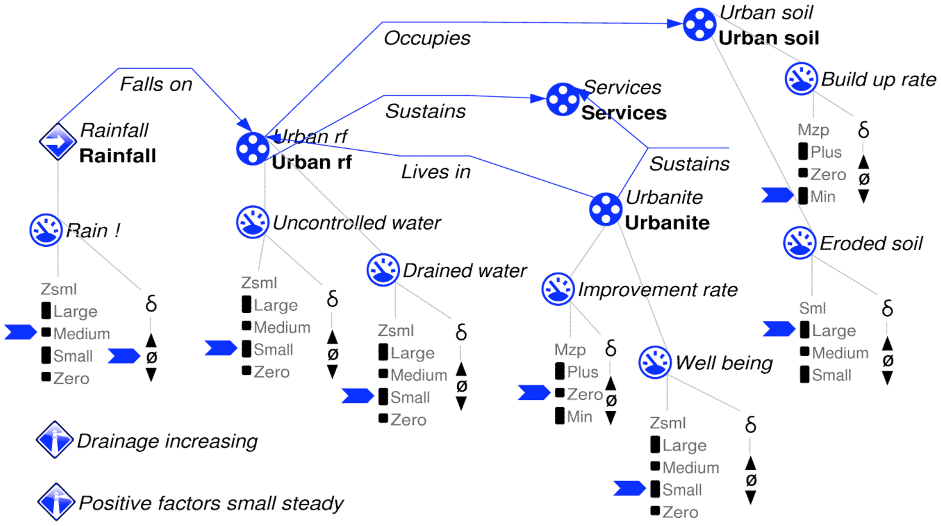
Table UD.08. Simulation summary: scenario ‘Drainage zero, economy and well being’.

3.2.5 Drainage (zero / increasing) economy, well being and soil

The last pair of scenarios produce the most complex simulations supported by the Urban Drainage submodel. They involve all the entities, 14 quantities and almost all the model fragments in the library. Figure UD.20 shows the two initial scenarios, in which it is assumed that (a) the drainage system does not exist; or (b) it exists and its capacity is increasing:



(a)



(b)

Figure UD.20. Initial scenarios (a) ‘Drainage zero, economy, well being and soil’; and (b) ‘Drainage increasing, economy, well being and soil’.

The simulation obtained with the scenario 'Drainage zero, economy, well being and soil' (Figure UD.20.a) is summarized in Table UD.09:

Scenario name	'Drainage zero, economy, well being and soil'
Full simulation	69 states
Initial states	[1, 2, 3, 4, 5]
End states	[4, 6, 27, 62]
Relevant behaviour path	[1→9→14→32→41→34→37→64→65→62]
Behaviour description	*Uncontrolled water*, *Flooded area*, *Transported garbage*, *Economic damage* and *Negative factors* follow the same beahviour: they start increasing, and reach the value *Large* in state 32. *Eroded soil* starts decreasing but, due to the contrary influences, it becomes stable in state 41 and then increases, until it reaches the value *Large* in state 64. Finally, *Well being* is stable in the initial state and in state 9 it starts decreasing. In state 65 its value changes to *Medium* and reaches *Small* in the final state.

Table UD.09. Simulation summary: scenario 'Drainage zero, economy, well being and soil'.

The scenario 'Drainage increasing, economy, well being and soil' (Figure UD.20.b) produces a simulation with 59 states, being one initial state and three end states [39, 43, 54]. The behaviour graph of this simulation is shown below:

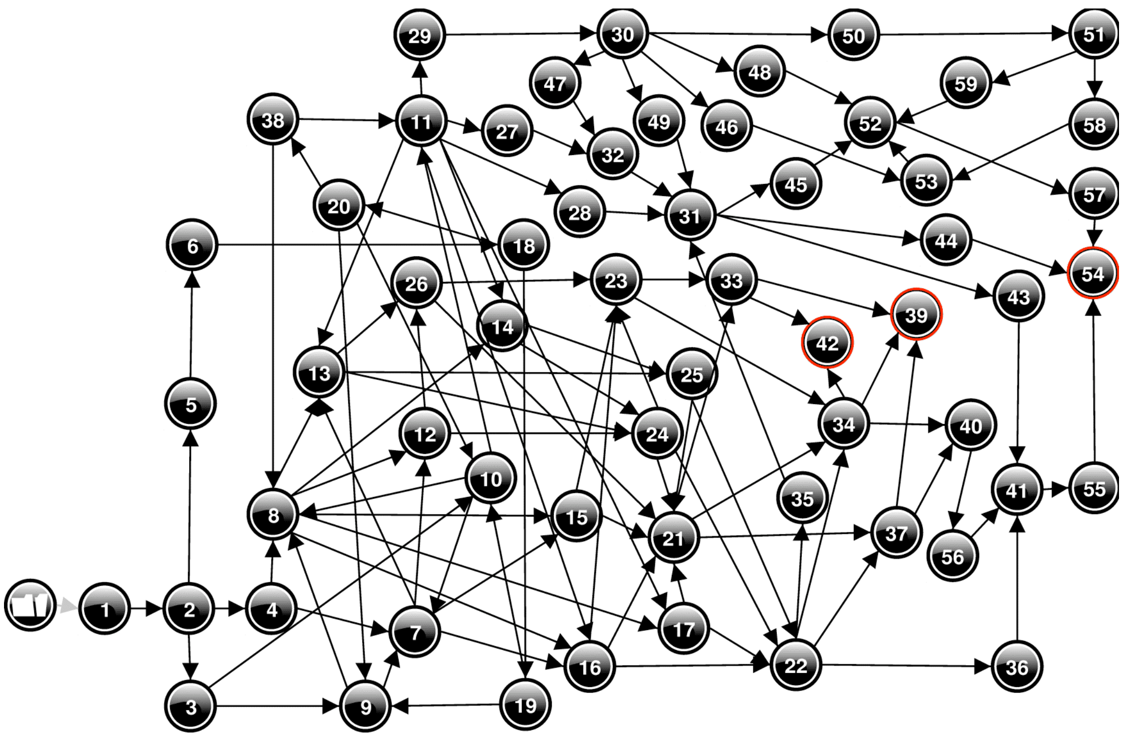


Figure UD.21. Behaviour graph obtained in a simulation with the scenario 'Drainage increasing, economy, well being and soil'.

Figure UD.22 presents the detailed causal model as it appears in state 13:

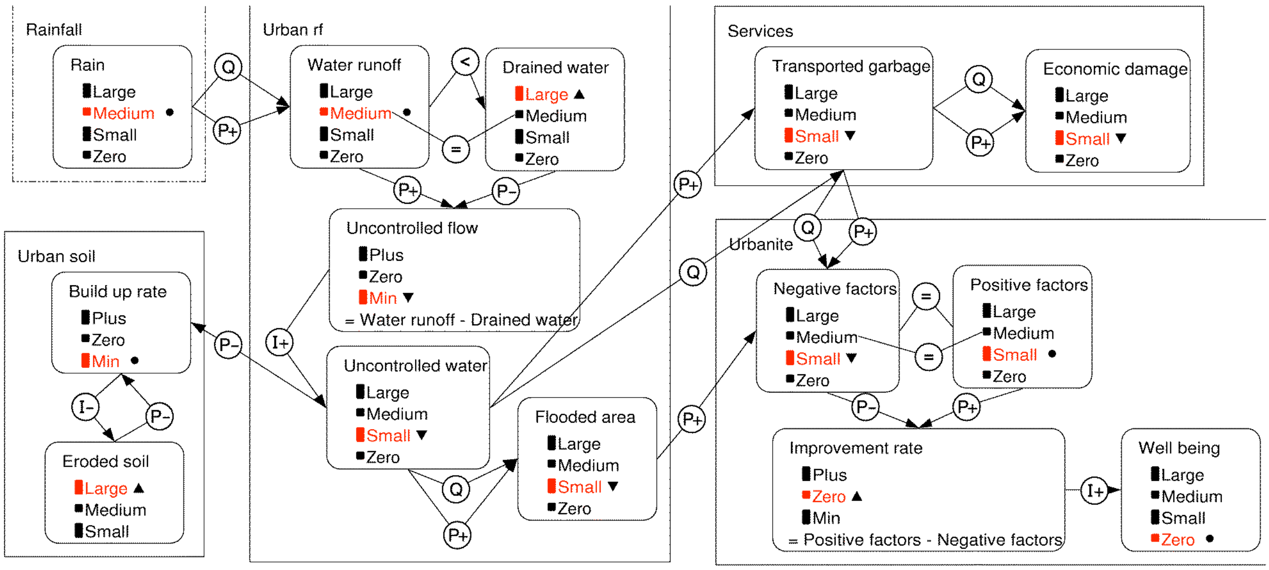


Figure UD.22. Detailed representation of the causal model in state 13 of the simulation started with the scenario 'Drainage increasing, economy, well being and soil'.

A selected behaviour path ([1→2→5→6→18→20→38→11→29→30→46→ 53→ 52→ 57→54]) shows clearly how the effects of the drainage system propagates to the main factors considered in this model:

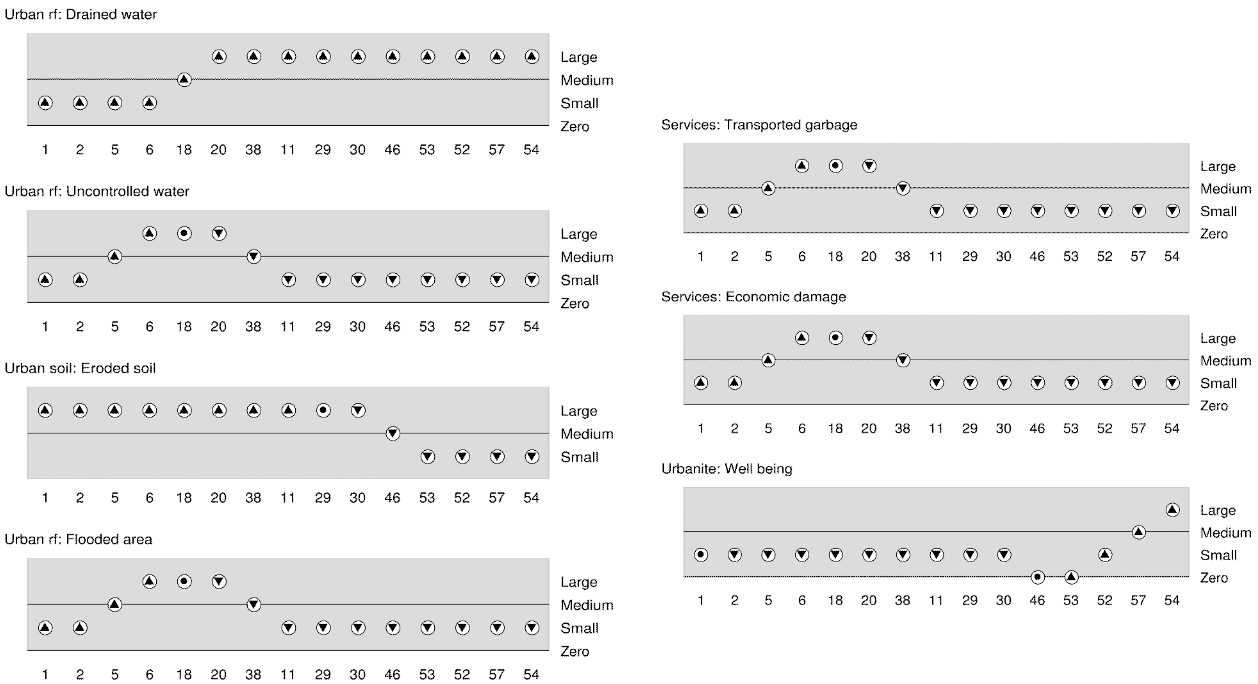


Figure UD.23. Value history diagrams of selected quantities in a behaviour path of the simulation starting with the scenario 'Drainage increasing, economy, well being and soil'.

Figure UD.23 shows that *Drained water* starts increasing and keeps this tendency, as it is an assumption included in the initial scenario. However, its effects are not immediate: *Uncontrolled water* is increasing during the first four states, and becomes stable in state 18. The actual decrease in the undesired water flow starts in state 20, and goes that way until the end of the simulation. The quantities *Flooded area*, *Transported garbage*, *Economic damage* and *Negative factors* follow the same behaviour shown by *Uncontrolled water*. *Eroded soil* presents a different behaviour: it increases until state 11 and in state 29 it becomes stable. After that *Eroded soil* decreases and reaches the interval of values *Small* in state 53 and continues decreasing within this interval until the end state. And how these changes affect *Well being*? This quantity starts stable, and then decreases within the interval *Small* until state 30. In state 46 it goes to the lowest value, *Zero*, and stabilizes, to start increasing in state 53. After this re-start, it continues to increase and reaches its maximum value at the end state.

In order to understand why the changes in the derivative of *Well being* came about, it is interesting to follow the changes in the inequality relations that govern the calculations of *Uncontrolled flow* (see section 3.1.4) and *Improvement rate* (see section 3.1.15). These informations are given by the equation history of the selected behaviour path, shown in Figure UD.24:

Water runoff (Urban rf) ? Drained water (Urban rf)

>	>	>	>	=	<	<	<	<	<	<	<	<	<	<
1	2	5	6	18	20	38	11	29	30	46	53	52	57	54

Positive factors (Urbanite) ? Negative factors (Urbanite)

=	<	<	<	<	<	<	<	<	<	=	>	>	>	>
1	2	5	6	18	20	38	11	29	30	46	53	52	57	54

Figure UD.24. Equation history diagrams showing inequality changes between the quantities *Water runoff* and *Drained Water*, and *Positive factors* and *Negative factors*, in a selected behaviour path.

Figure UD.24 shows the inequality values between *Positive factors* and *Negative factors* significantly changing in states 30, 46 and 53. Although the magnitudes of the two quantities had value *small* in these states (see the values of all quantities in the full simulation with this scenario in the Appendix), *Positive factors* was actually smaller than *Negative factors* between state 2 and state 30. However, given the continuous negative influence coming from *Transported garbage* and *Flooded area* (see the causal model in Figure UD.22), *Negative factors* had value <*small*, *minus*> and its magnitude became equal to *Positive factors* in state 46. As the influence on *Negative factors* was still active, this quantity became smaller than *Positive factors* in state 53. These inequality changes cause the value of the magnitude of *Improvement rate* to move from *Minus* to *Zero* and then to *Plus*, respectively in states 30, 46 and 53 (see the Appendix). Finally, changes in the magnitude of *Improvement rate* explain why the derivative of *Well being* changed in these states from decreasing to stable and next to increasing, respectively.

Additional details about this simulation can be found in the Annex (section 9).

4 Submodel Springs

The submodel Springs (SP) explores an important problem caused by the urbanization process. Accordingly, the land type is characterized as being semi-urbanized, that is, it represents parts of the Riacho Fundo basin where urban settlements of increasing size are mingled with small farms, in which the agricultural production is manufactured in food and raw material industries. Assuming that the volume of water coming from internal underground sources is constant, this change in the land use causes the soil to become impermeable, so that the infiltration of water is reduced and therefore the amount of underground water is also reduced. These changes are also responsible for the disappearance of springs and for the reduction on the amount of the water in rivers.

The submodel should provide answers for the question: *how changes in soil features, under the conflicting forces of urbanization and natural vegetation dynamics, may affect functional springs, rivers and the industrial production in the Riacho Fundo basin?*

4.1 Model fragments

The library of components of this submodel consists of 18 model fragments, being nine static and nine model fragments related to processes. No agents are used in this case.

4.1.1 Semi-urban Riacho Fundo

The basic structure of the semi-urban environment representation is shown in the model fragment 'Semi-urban Riacho Fundo'. It introduces the configuration involving the entities 'Semi urban rf', 'Semi urban soil' and 'Vegetation', and the quantities *Biological pressure* on the soil coming from the vegetation, the *Urbanization pressure* on the soil coming from urbanized areas, and the *Level of aggregation* of the soil particles:

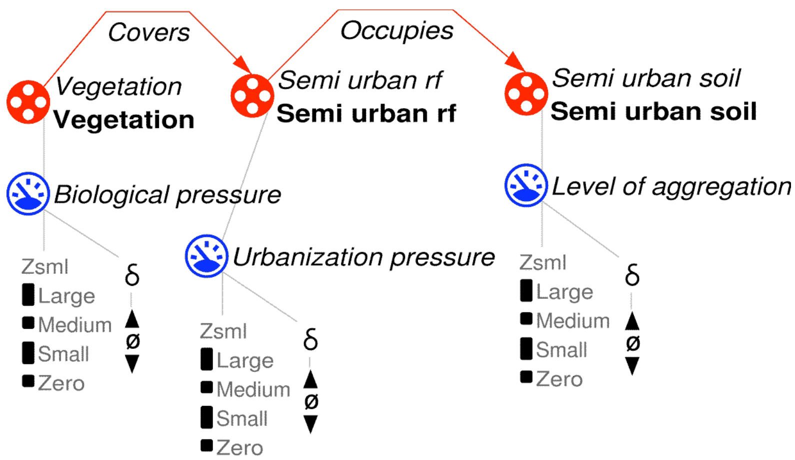


Figure SP.01. Static model fragment 'Semi-urban Riacho Fundo'.

4.1.2 Soil aggregation process

This model fragment is used to define the aggregation of soil particles process, introducing the quantity *Particle aggregation rate*:

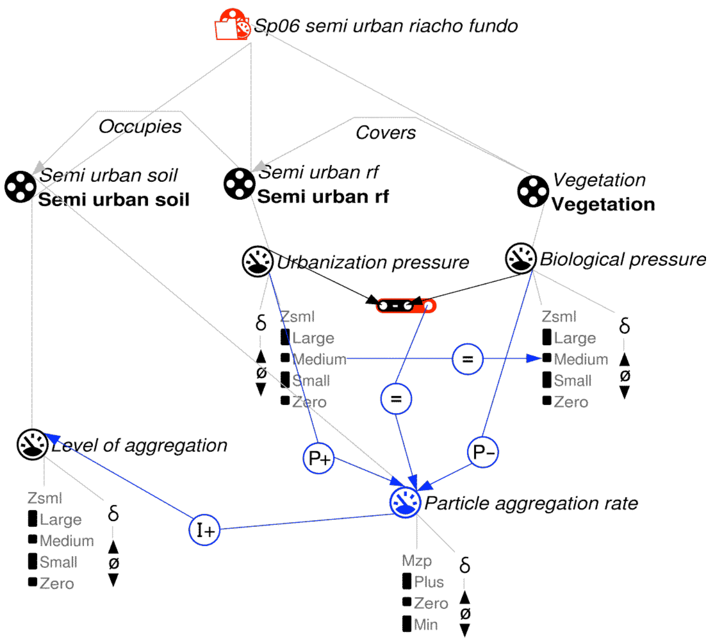


Figure SP.02. Process model fragment 'Soil aggregation process'.

For the same reason already discussed in section 3.1.15, three additional model fragments were included in the library as children of this model fragment. They do not introduce new features in the simulation as they only have, as conditions, inequalities stating that *Urbanization pressure* is equal, greater than and smaller than *Biological pressure*.

4.1.3 Soil properties

The entity 'Semi urban soil' has two subtype entities, 'Surface' and 'Underground' to characterize different spatial regions (see section 2.1). The former is structurally related to the top of the soil and the latter located below the top of the soil. Each entity is associated to an instance of the quantity *Amount of water*, while the already mentioned quantity *Level of aggregation* is associated to any type of 'Semi urban soil'. These concepts are represented in the model fragment 'Soil properties':

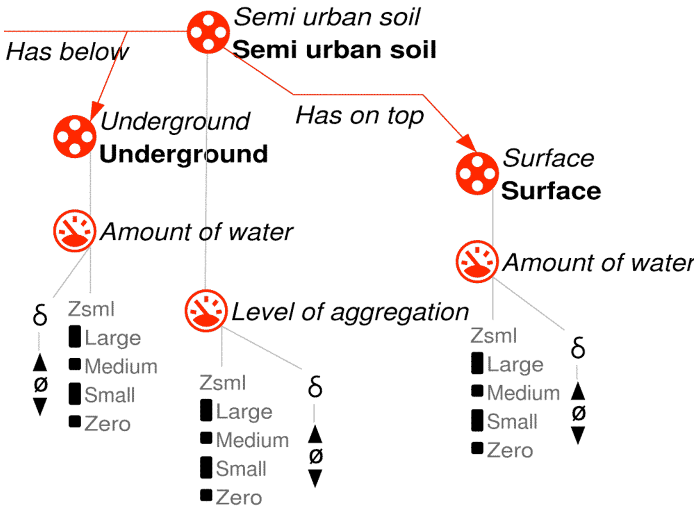


Figure SP.03. Static model fragment 'Soil properties'.

4.1.4 Water bodies

The model fragment 'Water body' introduces the entity 'Water' and the quantity *Amount of water* associated to it. This way, whenever the subtype entities 'River', 'Spring' and 'Stream' are included in the simulation (see section 2.1), they already have this quantity associated to them.

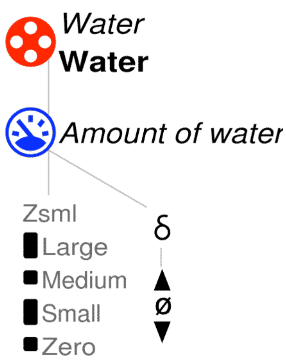


Figure SP.04. Static model fragment 'Water body'.

4.1.5 Infiltration process

The infiltration process causes the *Amount of water* on the surface to decrease and the *Amount of water* on the underground to increase. This is actually a tricky phenomenum. The quantity *Infiltration rate* is influenced by three quantities: positively by the *Amount of water* in the surface of the soil, and negatively by both *Amount of water* at the underground and by the *Level of aggregation* of the soil particles. This way, the rate increases when the amount of water in the surface increases (and so does the pressure it causes, not represented in the submodel), and decreases when the resistance due to the amount of water at the underground and the particle aggregation level increases. There are also two negative feedback loops from the two quantities *Amount of water* on the *Infiltration rate* that control the flow. Although they have the same final effect (to reduce the rate), they rely on different mechanisms, as the rate causes the water on the surface to drecrease, and the underground water to increase. Finally, the process can only be active when there is water at the surface – when the latter is zero, so is the *Infiltration rate*. These concepts are described by the following model fragment:

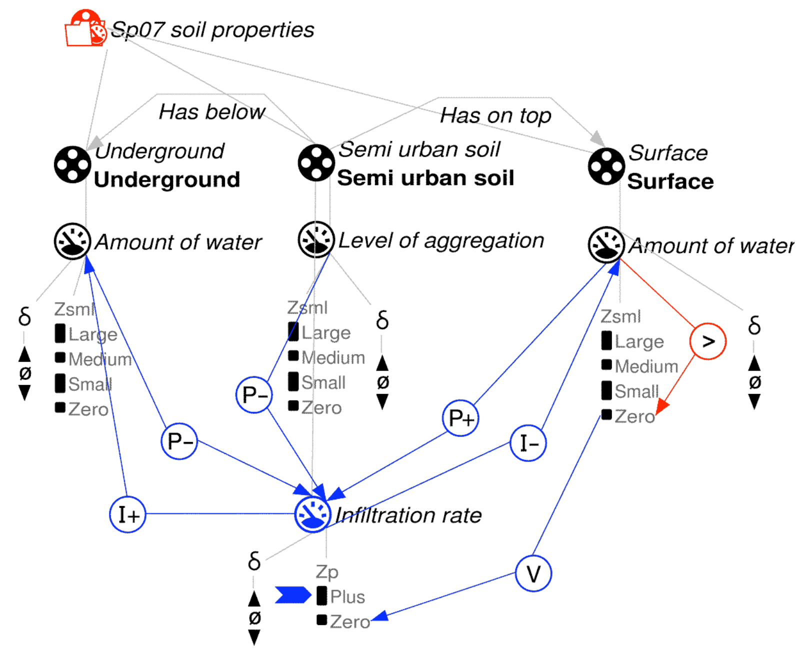


Figure SP.05. Process model fragment 'Infiltration process'.

4.1.6 Functional springs

The submodel establishes that (a) the entity 'Surface' contains the entity 'Spring'; (b) the water that flows in such water body comes from the entity 'Underground'; and (c) the amount of water flowing in the springs corresponds to the amount of underground water available. This knowledge is captured in the following model fragment:

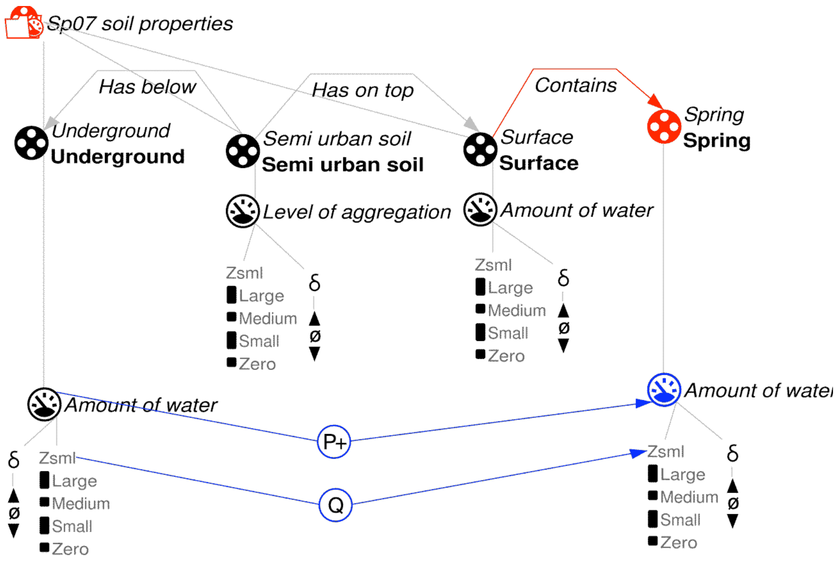


Figure SP.06. Static model fragment 'Functional springs'.

4.1.7 River configuration

The model fragment 'River configuration' introduces the entity 'River' and assumes that the *Amount of water* in the river correspond to the amount of water that comes from the springs. This implements a commonsense association between what is happening to the springs and to the rivers:

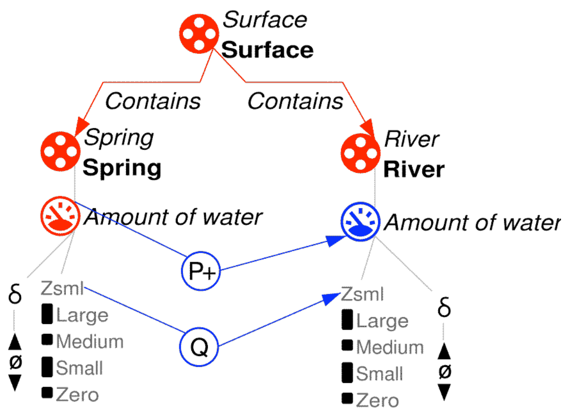


Figure SP.07. Static model fragment 'River configuration'.

4.1.8 Industry configuration

This model fragment introduces the entity 'Industry', along with its associated quantities *Resource inflow*, *Resource consumption* and *Industrial products*:

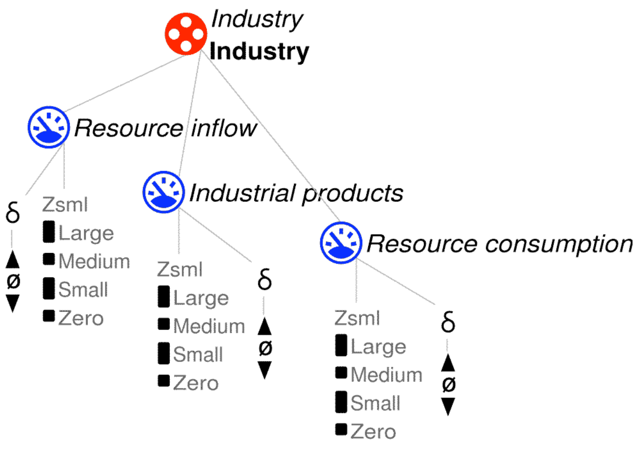


Figure SP.08. Static model fragment 'Industry configuration'.

4.1.9 Industry requires water

Industrial production certainly requires a number of raw materials, but the current version of this submodel considers only water. It is supplied by undergroung water, as it is common for the industries in the Riacho Fundo to dig wells to support their activities. Note also that this model fragment introduces a directed correspondence between the derivatives of underground *Amount of water* and industrial *Resource Inflow*. As a consequence, both quantities change in the same direction (both are increasing, stable or decreasing simultaneously), even if there are other influences in the latter quantity, and the complexity of the simulation is reduced. This knowledge is represented as follows:

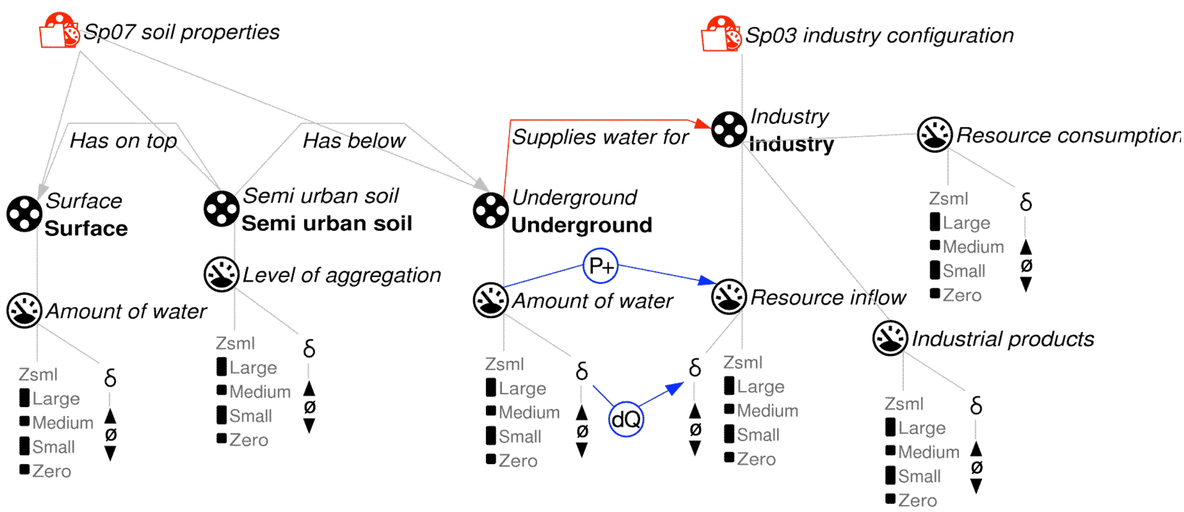


Figure SP.09. Static model fragment 'Industry requires water'.

4.1.10 Assume industry consumption constant

This model fragment implements the assumption that industrial consumption of resources (raw materials, human labour, technological support, financial investments, energy) is constant throughout the simulation. This assumption means that the industry is working in the limit of its capacity. However, note that the magnitude of industry capacity can be changed (the resource consumption can be *Small*, *Medium* or *Large*), as the constraint is put on the *Resource consumption* derivative. Having the assumption included in the model, changes in industrial production are related the resources inflow, in particular to changes in water availability. This approach gives the possibility of running different simulations with different values for the rate of industrial production (see the section 4.1.11 below).

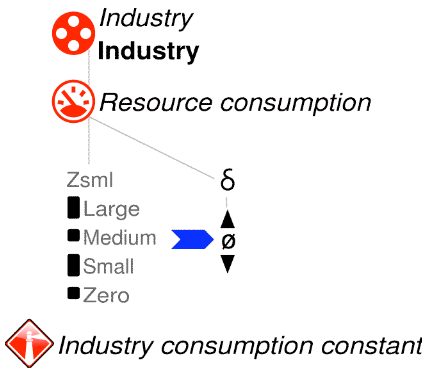


Figure SP.10. Static model fragment 'Assume industry consumption constant'.

4.1.11 Industrial production process

Finally, the basic structure adopted for representing economic processes in the Riacho Fundo integrated model is applied to industries: the rate of the industrial production is calculated from the difference between inflow and consumption of resources:

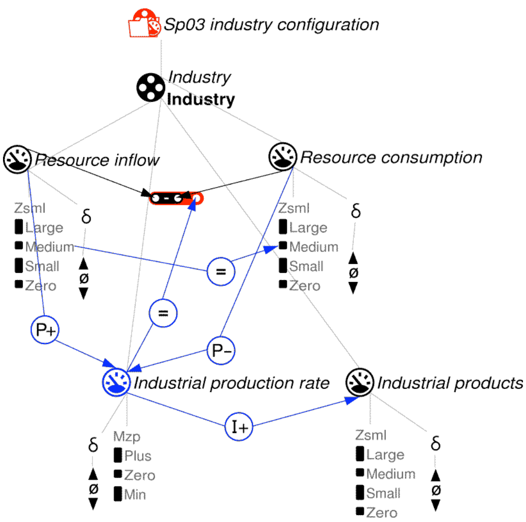


Figure SP.11. Process model fragment 'Industrial production process'.

As in the 'Soil aggregation process' (see section 4.1.2), three additional model fragments were included in the library, stating that *Resource inflow* is equal, greater than and smaller than *Resource consumption*.

4.2 Scenarios and simulations

The submodel has seven scenarios that produce simulations of increasing complexity. Summaries of four simulations and details of two simulations are presented in this section. A simulation exploring the industrial production process alone is not discussed here. Note that in all the scenarios, the quantities *Biological pressure* and *Urbanization pressure* are followed by the exclamation mark that indicates these quantities have exogenously defined behaviour. In all the simulations, *Urbanization pressure* has magnitude constant and derivative set to zero (it is steady). With respect to the quantity *Biological pressure*, it has an exogenously driven behaviour defined in each scenario. Finally, for better understanding the analyses of the simulations, it may be useful to consult the causal model for the Springs submodel, presented in section 4.2.6 (Figure SP.20).

4.2.1 Semi urban (steady) and vegetation pressure (exogenous)

This scenario starts the simplest simulation with the Springs submodel. The simulation involves four quantities only. However, in order to create more complex simulations that may have some educational added value, it is assumed the quantity *Biological pressure* expresses exogenously driven behaviours 'generate all values' and 'sinusoidal'. In this case, in every state all possible values of this quantity's magnitude are automatically generated and its derivative is set to express the sinusoidal behaviour, which results in cyclic patterns of behaviour paths.

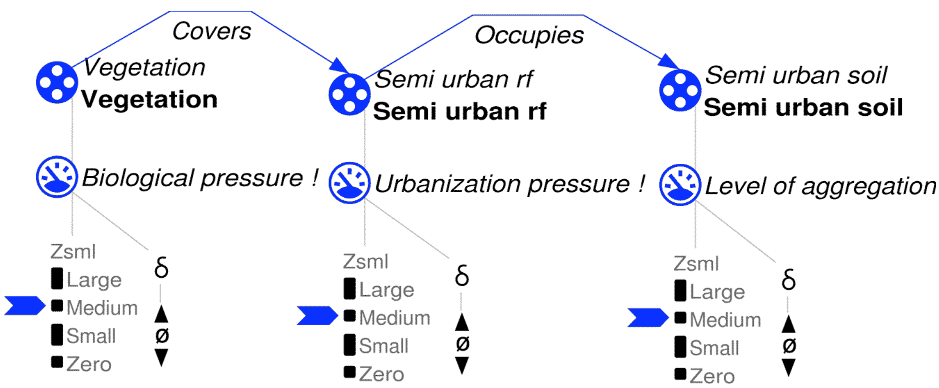


Figure SP.12. Initial scenario 'Semi-urban (steady) and vegetation pressure (generate all magnitude values and derivative sinusoidal)'.

Scenario name	‘Semi-urban (steady) and vegetation pressure (generate all magnitude values and derivative sinusoidal)’
Full simulation	29 states
Initial states	[1,2]
End states	there are no end states
Relevant behaviour path	[24→9→13→14→19→20→16→17→22→24]
Behaviour description	While the *Urbanization pressure* is constant and steady with the value <*Medium*, *zero*>, the other three quantities show the typical cyclic behaviour. *Biological pressure* starts decreasing, reaches the value *Medium* in state 13 and *Zero* in state 19. It starts increasing in state 20, gets the value <*Large*, *Zero*> in state 22 and the same value <*Large*, *Minus*> as in the beginning of the cycle. The *Level of aggregation* value history diagram presents a smooth sinusoidal curve.

Table SP.01. Simulation summary: initial scenario ‘Semi-urban (steady) and vegetation pressure (generate all magnitude values and derivative sinusoidal)’.

4.2.2 Semi urban (steady) and vegetation pressure (random)

This scenario appears to be exactly the same as the one shown in Figure SP.12, except for the exogenous behaviour of *Biological pressure* that is now a combination of generate all values (of magnitude) and random derivative, that is, its derivative can assume all possible values in each state. It results in a more complex simulation, as the quantities may express the cyclic behaviour but can also move forward and backward within the same value interval. The simulation produces three initial states and 37 states in total. There is only one end state, 24. The behaviour graph is shown below:

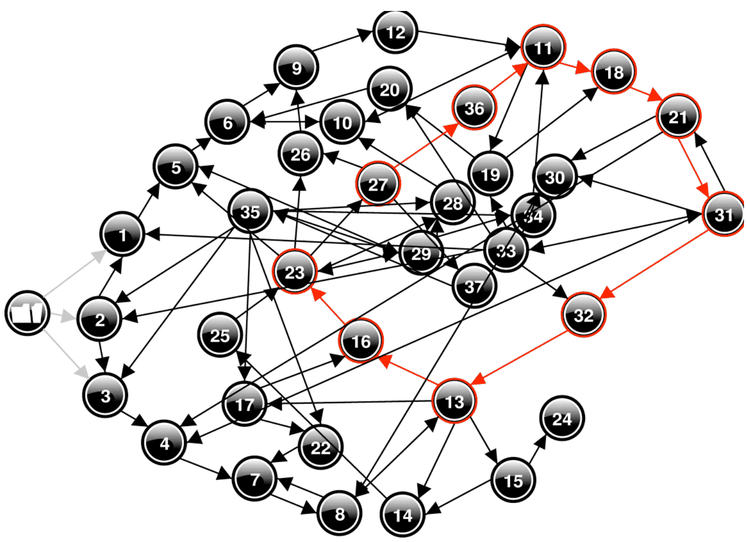


Figure SP.13. Behaviour graph of the simulation that starts with the initial scenario ‘Urban (steady) and cover (random)’.

The value history diagrams for the four quantities involved in the model, as they appear in the behaviour path [32→13→16→23→27→36→11→18→21→31→32], are presented in Figure SP.14:

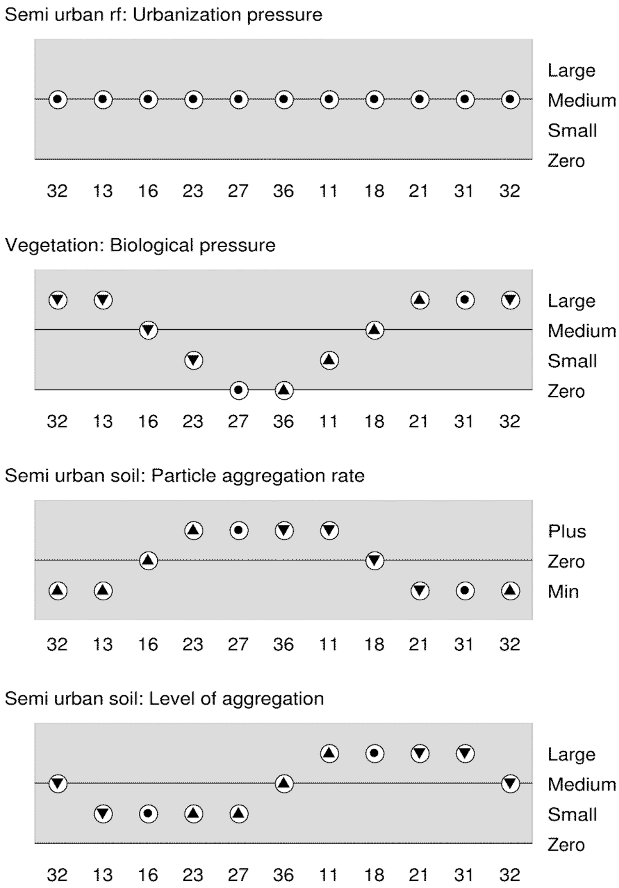


Figure SP.14: Value history diagrams of four quantities in a seleted behaviour path of the simulation with the initial scenario ‘Semi urban (steady) and vegetation pressure (random)’.

The random behaviour can be noticed in states 21 and 31. The behaviour graph (Figure SP.13) shows two arrows pointing in opposite directions between these two states. It means that the exogenous influenced quantity can oscillate from one state to the other: *Biological pressure* can go from <*Large*, *Plus*> to <*Large*, *Zero*> and vice-versa.

4.2.3 Semi urban cover and infiltration

This scenario introduces the infiltration process and correspondent state variables *Amount of water*, associated to the entities ‘Surface’ and ‘Underground’. As a consequence, seven quantities are involved in the simulation. The quantities *Urbanization pressure* and *Biological pressure* are assumed to be exogenously driven constant and steady. As a consequence, the *Particle aggregation rate* takes the value <*Zero*, *Zero*> and the quantity *Level of aggregation* remains stable (in this case, with the value <*Medium*, *Zero*>).

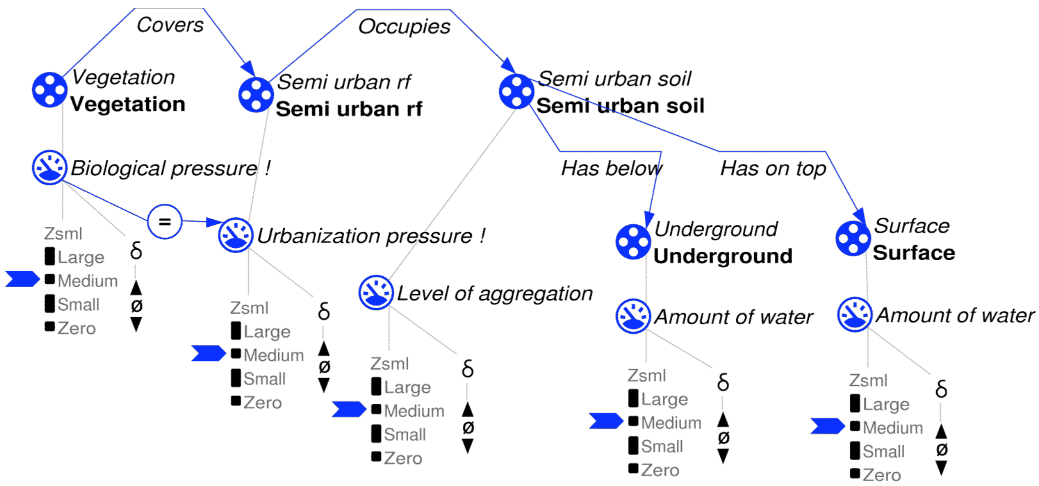


Figure SP.15: Initial scenario ‘Semi urban cover and infiltration’.

Scenario name	‘Semi-urban cover and infiltration’
Full simulation	3 states
Initial states	[1]
End states	[3]
Relevant behaviour path	[1→2→3]
Behaviour description	*Infiltration rate* has value <*Plus*, *Minus*> and decreases until state 3, when it becomes <*Zero*, *Zero*>. Surface *Amount of water* starts in <*Medium*, *Minus*> and decreases up to <*Zero*, *Zero*, while underground *Amount of water* starts in <*Medium*, *Plus*> and decreases to <*Zero*, *Zero*>.

Table SP.02. Simulation summary: initial scenario ‘Semi-urban cover and infiltration’.

4.2.4 Semi urban cover, infiltration and spring

In this scenario the entity ‘Spring’ is added to the system structure. This way, the simulation now involves eight quantities. The same conditions of the previous scenario (see section 4.2.3) apply to the calculation of the aggregation level of soil particles.

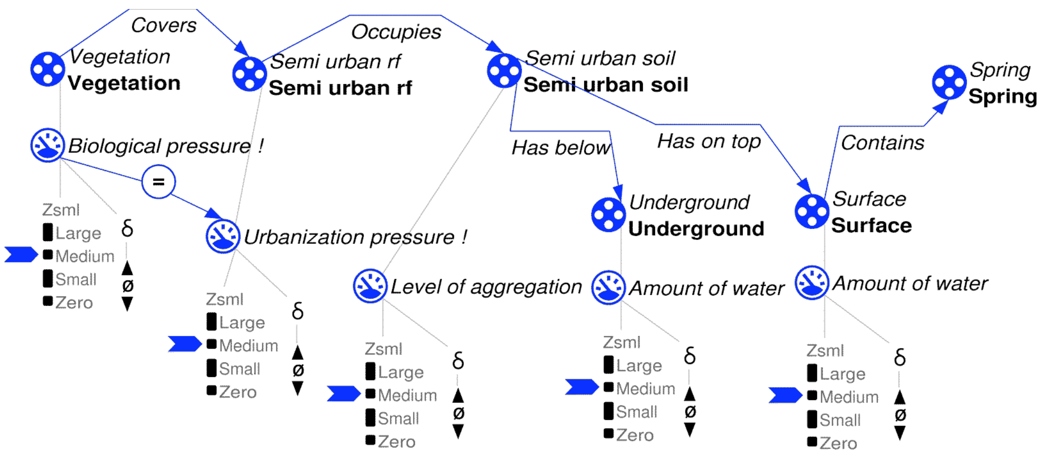


Figure SP.16. Initial scenario ‘Semi-urban cover, infiltration and spring’.

Scenario name	'Semi-urban cover, infiltration and spring'
Full simulation	3 states
Initial states	[1]
End states	[3]
Relevant behaviour path	[1→2→3]
Behaviour description	The behaviour of the quantities *Infiltration rate*, *Amount of water* at the surface and at the underground are the same as described in the previous simulation. The *Amount of water* in the springs has the same behaviour as the underground water.

Table SP.03. Simulation summary: initial scenario 'Semi-urban cover, infiltration and spring'.

4.2.5 Semi urban cover, infiltration, spring and river

The entity 'River' is added to the system structure in this scenario, and the simulation now involves nine quantities. The same conditions of the previous two scenarios (see section 4.2.3) apply to the calculation of the aggregation level of soil particles.

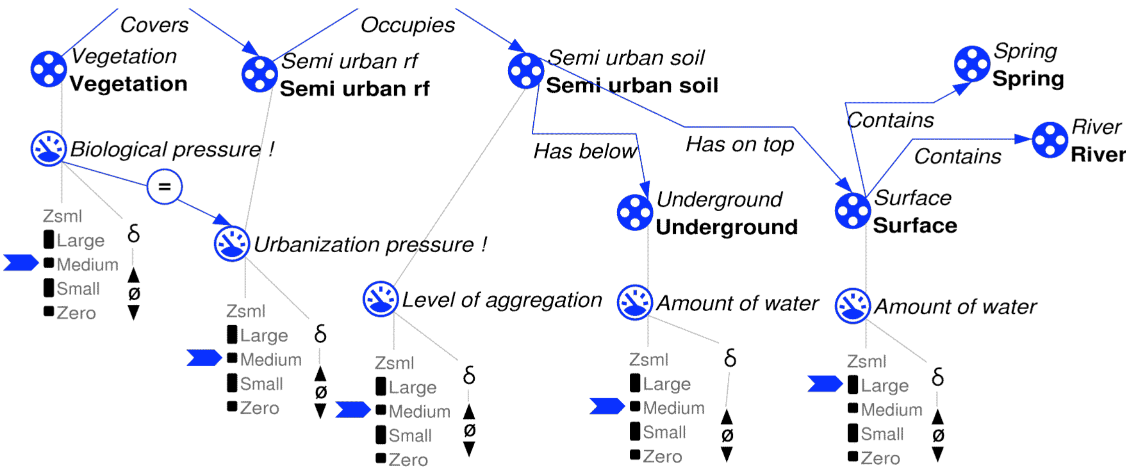


Figure SP.17. Initial scenario 'Semi-urban cover, infiltration, spring and river'.

Scenario name	'Semi-urban cover, infiltration, spring and river'
Full simulation	5 states
Initial states	[1]
End states	[5]
Relevant behaviour path	[1→2→3→4→5]
Behaviour description	Idem. The *Amount of water* in the river has the same behaviour as for the springs.

Table SP.04. Simulation summary: initial scenario 'Semi-urban cover, infiltration, spring and river'.

4.2.6 Semi urban cover, infiltration, spring, river and industry

The entity 'Industry' and three quantities (*Resource inflow*, *Resource consumption*, and *Industrial products*) are added to the system structure, and the assumption 'Industry consumption is constant' is included in this scenario. The simulation now involves all the 13 quantities of the submodel. The same conditions of the previous three scenarios (see section 4.2.3) apply to the quantities involved in the calculation of the aggregation level of soil particles.

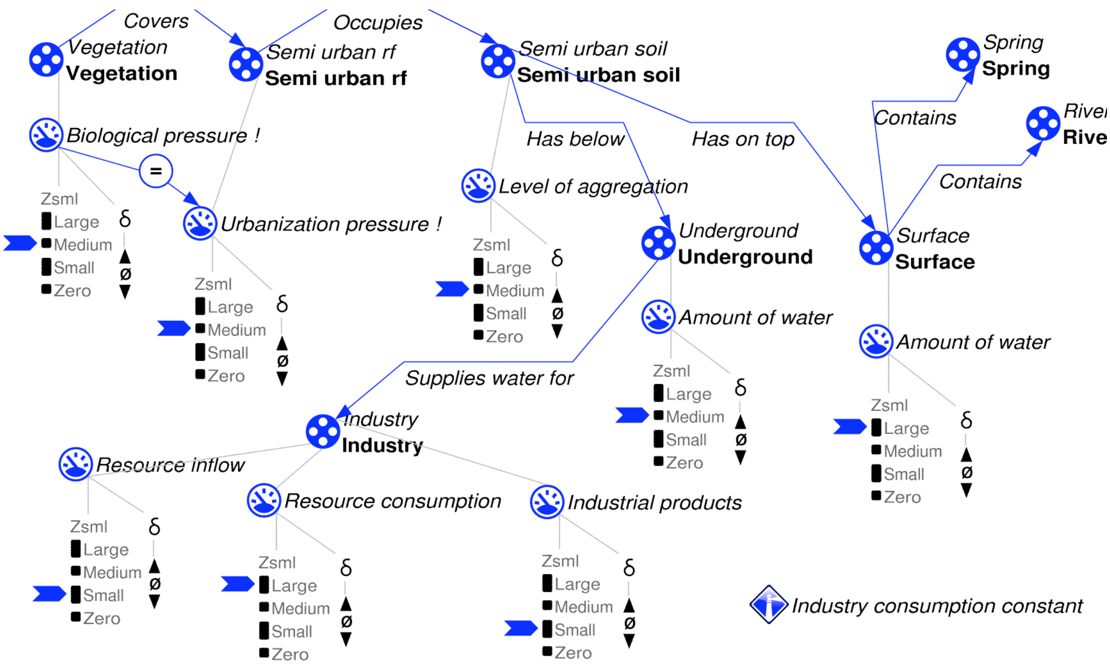


Figure SP.18. Initial scenario 'Semi-urban cover, infiltration, spring, river and industry'.

This scenario produces a simulation with one initial state, 37 states in the full simulation and seven end states ([14, 16, 17, 20, 21, 33, 31]). The behaviour graph is shown below:

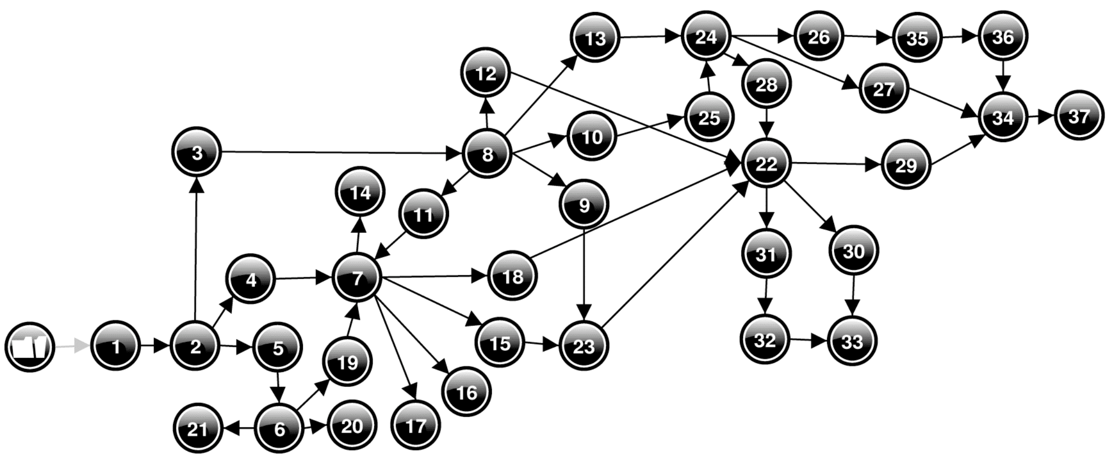


Figure SP.19. Initial scenario 'Semi-urban cover, infiltration, spring, river and industry'.

The following figure presents the causal model of the Springs submodel, as it is found in state 1 of this simulation:

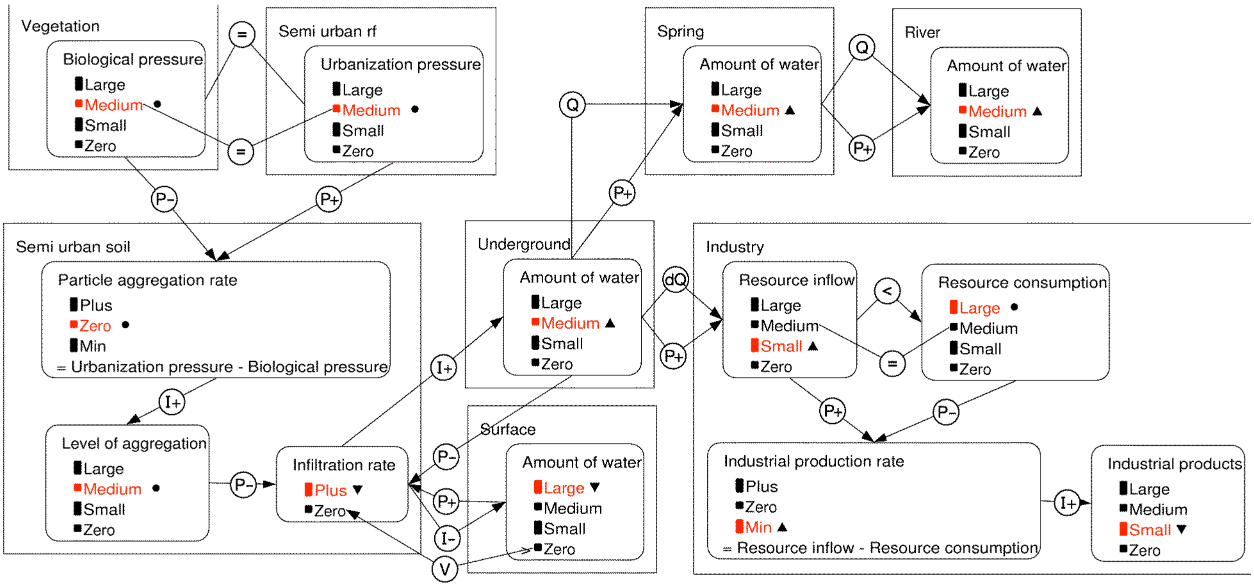


Figure SP.20. Causal model obtained in state 1 of the simulation starting with the initial scenario 'Semi-urban cover, infiltration, spring, river and industry'.

The values of the most relevant quantities in the behaviour path [1→2 →3→8 →13 →24 →27 →34 →37] are presented in Figure SP.21. The infiltration process is active between the states 1 and 34, being <*Plus*, *Minus*> the value of its rate. In state 37 it goes to <*Zero*, *Zero*>. Accordingly, the quantity *Amount of water* at the underground is increasing and moves from <*Medium*, *Plus*> to <*Large*, *Plus*> until the last state, when it gets the value <*Large*, *?*>, as the infiltration process is no longer active. At the surface, the *Amount of water* keeps the value <*Large*, *Minus*> until state 24, when it decreases sucessively to <*Zero*, *Zero*> in the end state. The quantities *Amount of water* in the spring and in the river follow the same behaviour expressed by the *Amount of water* at the underground.

In this simulation, the *Resource consumption* for the industrial production is assumed to be constant with the value <*Medium*, *?*>. The whole production process is influenced by the quantity *Amount of water* at the underground, and an interesting behaviour can be observed here: there are successive delays until the impact of this quantity affects *Resource inflow*, *Industrial production rate* and *Industrial products*. The quantity *Resource inflow* has the value <*Small*, *Plus*> in states 1 and 2, then move to <*Medium*, *Plus*> in state 3, and keeps the value <*Large*, *Plus*> until the state 34. In the end state, the value of *Resource inflow* is <*Large*, *?*> (see Figure SP.21).

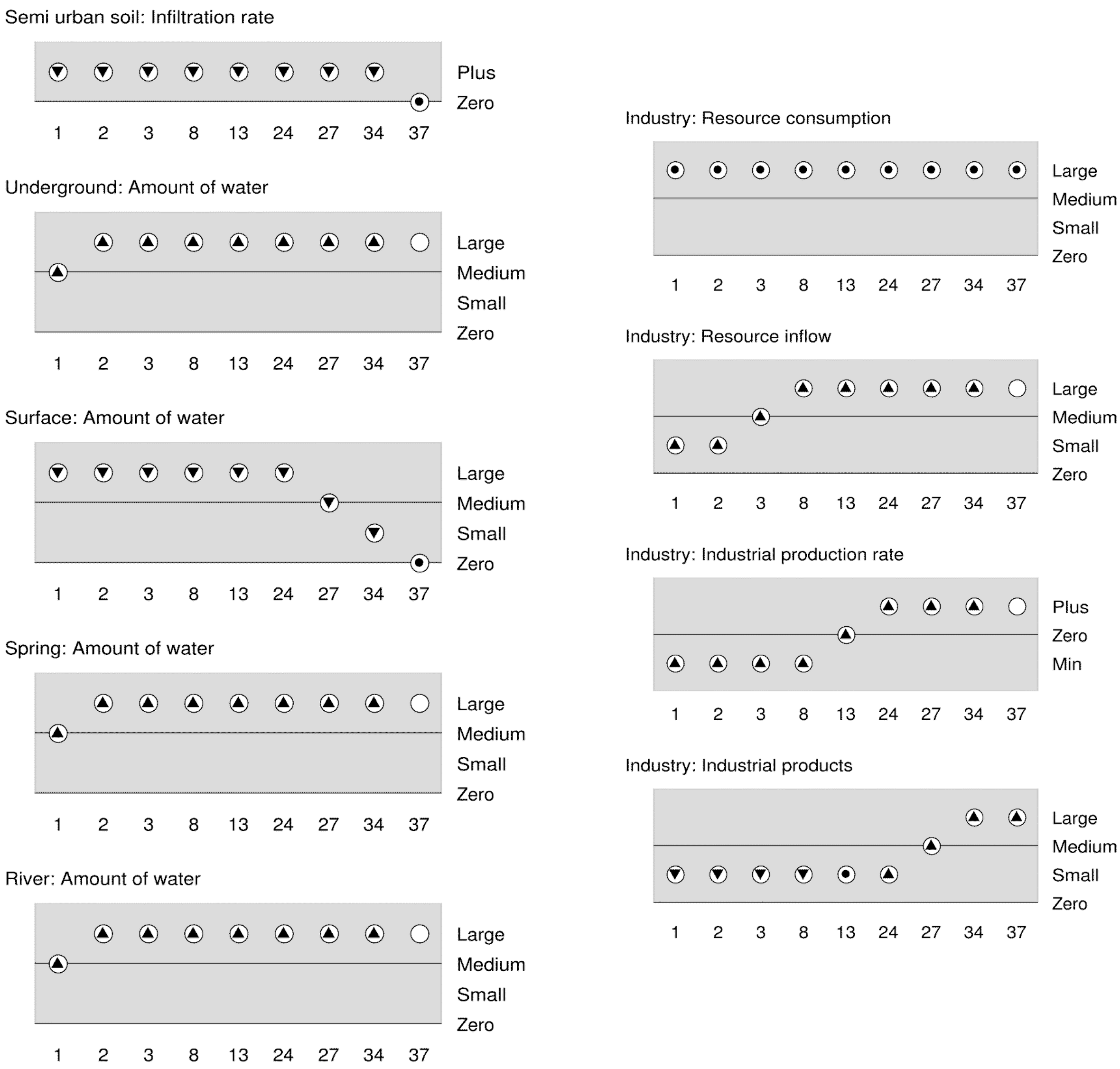


Figure SP.21 Value history diagrams of selected quantities in the simulation of the scenario ‘Semi-urban cover, infiltration, spring, river and industry’.

The quantity *Industrial production rate* has the value <*Minus*, *Plus*> until state 8, then move to <*Zero*, *Plus*> in state 13, and assumes the value <*Plus*, *Plus*> until the state 34 and, at state 37, its value is <*Plus*, *?*>. Finally, *Industrial products* is initially decreasing, and has value <*Small*, *Minus*> until state 8. In state 13, it stabilizes with value <*Small*, *Zero*> and has a positive derivative in state 24. From this point until the end of the simulatio, it increases, moving to <*Medium*, *Plus*> in state 27, and to <*Large*, *Plus*> in the last two states.

Additional details about this simulation can be found in the Annex (section 9).

5 Submodel Erosion

Erosion is a serious problem in the Riacho Fundo basin. It is caused by uncontrolled land occupation, unsustainable management techniques used by farmers, deforestation and lack of adequate drainage system. The perspective of the rural areas in the Riacho Fundo basin is taken in this submodel. The consequences can be diverse and include economic activities, water supply and biodiversity loss.

The simulations supported by this submodel should provide answers to the following question: *in the rural area of the Riacho Fundo basin, what are the effects of soil protection and erosion on agricultural production, on rivers and streams, and on animal biodiversity?*

5.1 Model fragments

The library of this submodel consists of 23 model fragments, being 11 about static features and 12 related to processes. No agents are used in this case.

5.1.1 Rural Riacho Fundo

The rural area of the Riacho Fundo basin is defined in this model fragment, that introduces the entity 'Rural rf' and the quantity *Vegetation cover*:

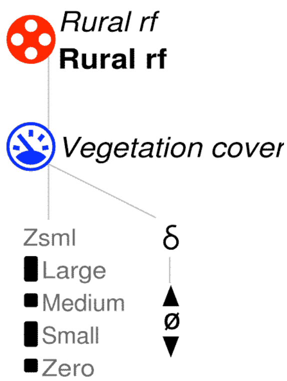


Figure ER.01. Static model fragment 'Rural Riacho Fundo'.

5.1.2 Vegetation configuration

The cluster of knowledge about the relations between the vegetation and the rural Riacho Fundo, that sets the conditions for the causal chain to start, is represented in this model fragment. It introduces the entity 'Vegetation', which 'covers' the 'Rural rf' basin, and two quantities, *Degradation* and *Regeneration* of the vegetation. The former refers to the loss of biomass due to natural processes, such as senescence and mortality, and human provoked processes, as deforestation and burning; the latter refers to the increment of biomass produced by natural process of reproduction, immigration of propagules, seed bank germination and somatic growth. Note that

Vegetation cover should be greater than zero as a condition for these quantities to exist, and the proportionalities relating *Vegetation cover* to *Degradation* (a negative influence) and to *Regeneration* (a positive influence):

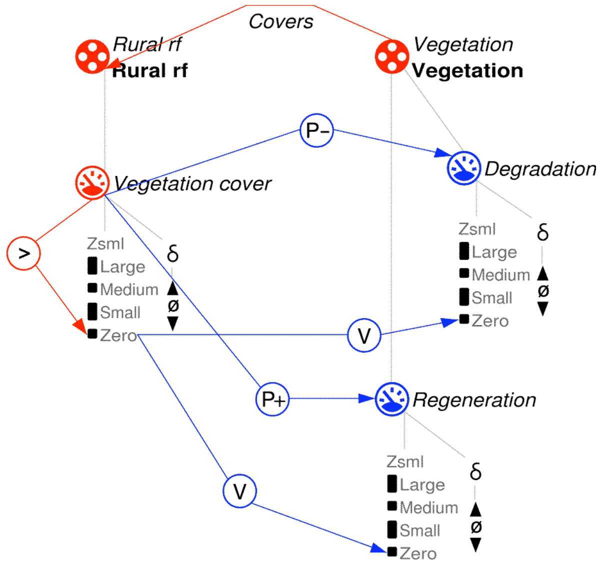


Figure ER.02. Static model fragment 'Vegetation configuration'.

5.1.3 Vegetation growth process

This model fragment defines the mechanism that leads to the vegetation growth process: *Degradation* is subtracted from *Regeneration* to calculate the *Vegetation growth rate*.

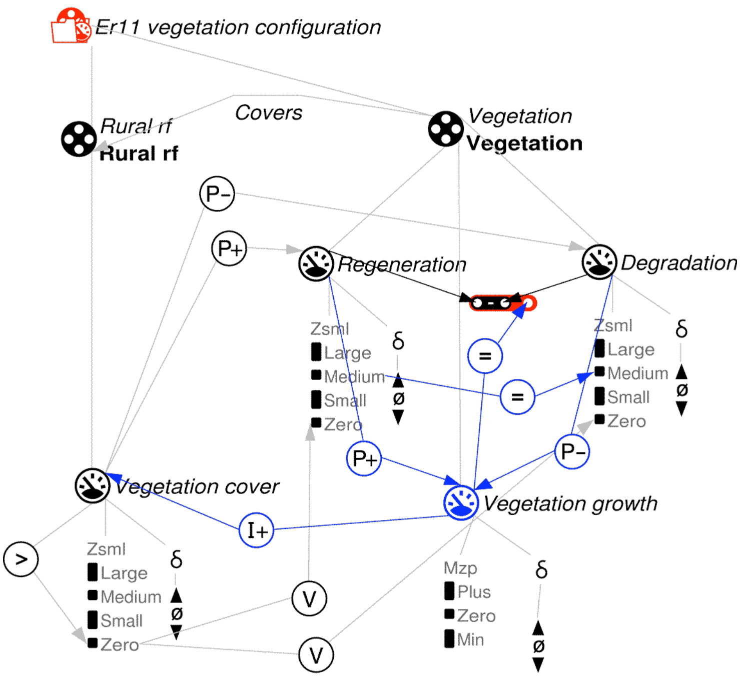


Figure ER.03. Process model fragment 'Vegetation growth process'.

As in similar processes (see, for example, sections 4.1.2 and 4.1.11), three additional children model fragments were included in the library, stating that *Resource inflow* is equal, greater than and smaller than *Resource consumption*.

5.1.4 Soil configuration

The entity 'Rural soil' and three related quantities, *Restoration rate*, *Erosion rate* and *Removed soil* are introduced by this model fragment. The first of these quantities represents the process of creating more soil as compensation for the removed soil by the erosion process. Although there are natural processes that in a way create soil, in the context of the Riacho Fundo basin it is more related to human actions (transporting soil from elsewhere, mixing different types of soil or adding manure to degraded soil) observed in some farms and degraded areas of the basin. And, of course, the success of soil restoration is heavily dependent on the vegetation cover. *Erosion rate* represents the rate of soil removal and *Removed soil* represents amount of soil that is actually transferred to other places.

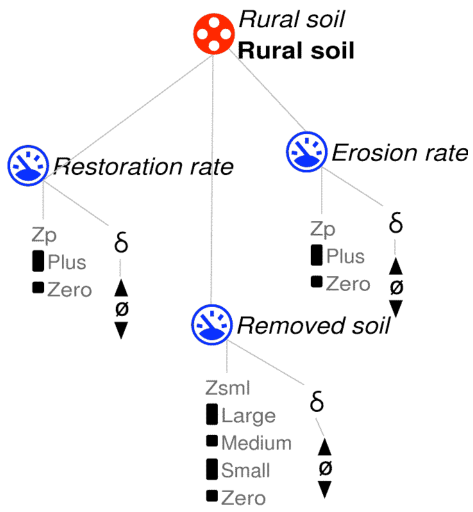


Figure ER.04. Static model fragment 'Soil configuration'.

5.1.5 Soil protection in the Riacho Fundo

This model fragment implements the idea that vegetation protects the soil, mostly by supporting the soil restoration. The proportionality expresses the notion that the increasing in vegetation cover speeds up the restoration process. The correspondence between the values *zero* in the quantity spaces of the two quantities expresses the notion that when the vegetation cover reaches the value zero, the restoration process should stop.

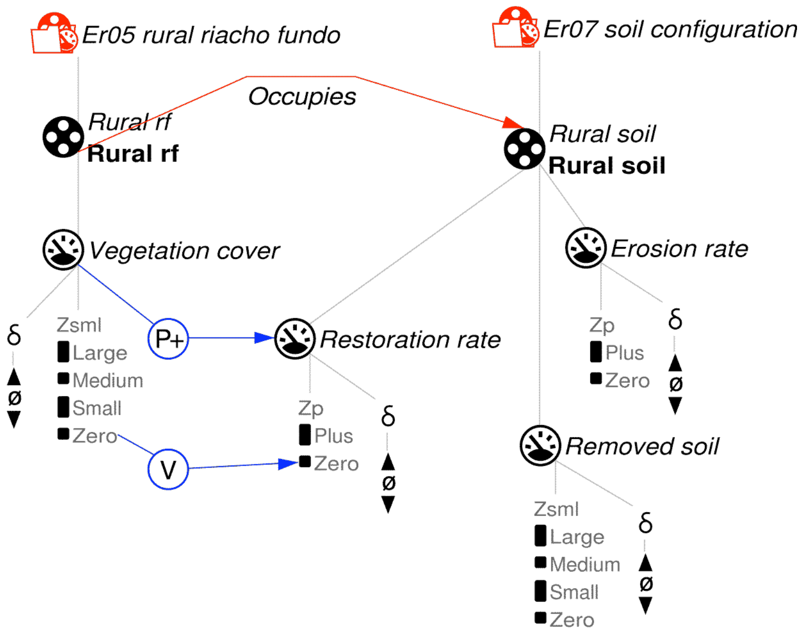


Figure ER.05. Static model fragment ‘Soil protection in the Riacho Fundo’.

5.1.6 Erosion and restoration processes

This model fragment implement the main soil processes of erosion and restoration. Note that it includes a feedback loop involving *Removed soil* and *Erosion rate*, expressing the notion that the increasing of the former increases the latter:

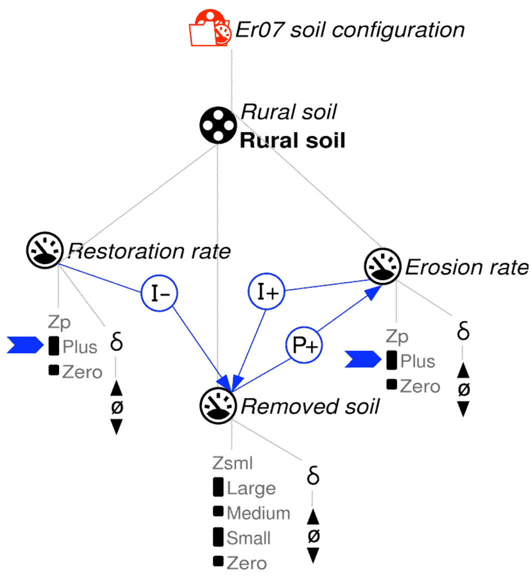


Figure ER.06. Process model fragment ‘Erosion and restoration processes’.

Three additional children model fragments were included in the library, stating that *Restoration rate* is equal to, greater than and smaller than *Erosion rate*.

5.1.7 Stream configuration

The basic properties of streams are represented in this model fragment, which introduces the quantities *Sediment*, *Amount of water* and *Stream depth*:

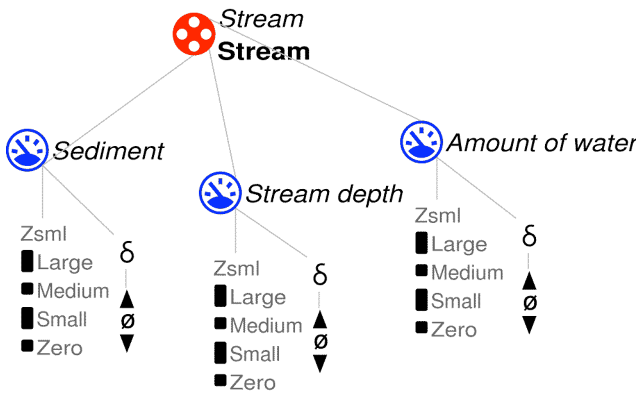


Figure ER.07. Static model fragment 'Stream configuration'.

5.1.8 Removed soil and stream

This model fragment defines how the effects of erosion propagates to the water body. The quantity *Sediment* is influenced by and corresponds to *Removed soil*. In the next step of the causal chain, the amount of sediments reduces the water body depth. Finally, the quantity *Amount of water* in the stream is influenced by and corresponds to *Stream depth*:

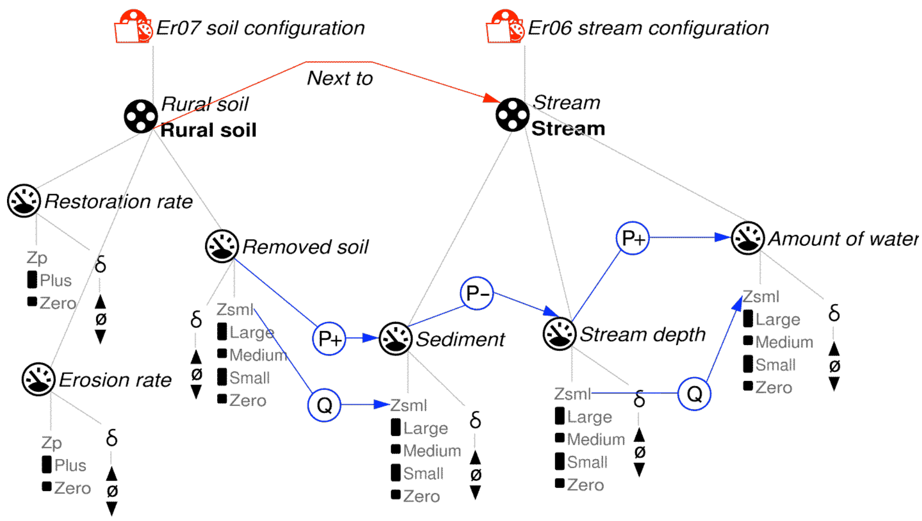


Figure ER.08. Static model fragment 'Removed soil and stream'.

5.1.9 Vertebrate survival and biodiversity

Water body conditions affect the survival of animals and, as a consequence, biodiversity. Knowledge about these topics is captured in two model fragments. The first one is 'Vertebrate survival and biodiversity'. It links the amount of biodiversity to the survival of vertebrate animals:

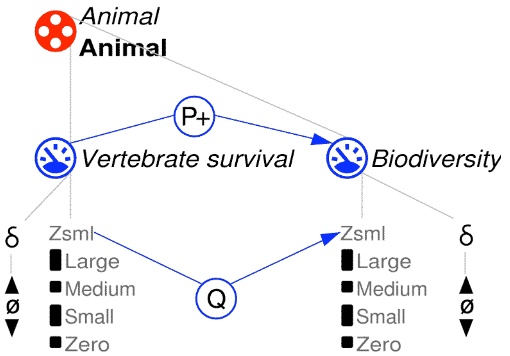


Figure ER.09. Static model fragment 'Vertebrate survival and biodiversity'.

5.1.10 Stream and vertebrate survival

The second model fragment is 'Stream and vertebrate survival', in which survival is assumed to be very much dependent on the depth of the water body. Note that this restrictive condition applies to the Riacho Fundo basin, where the survival of capybares depends on the causal chain represented in this model fragment:

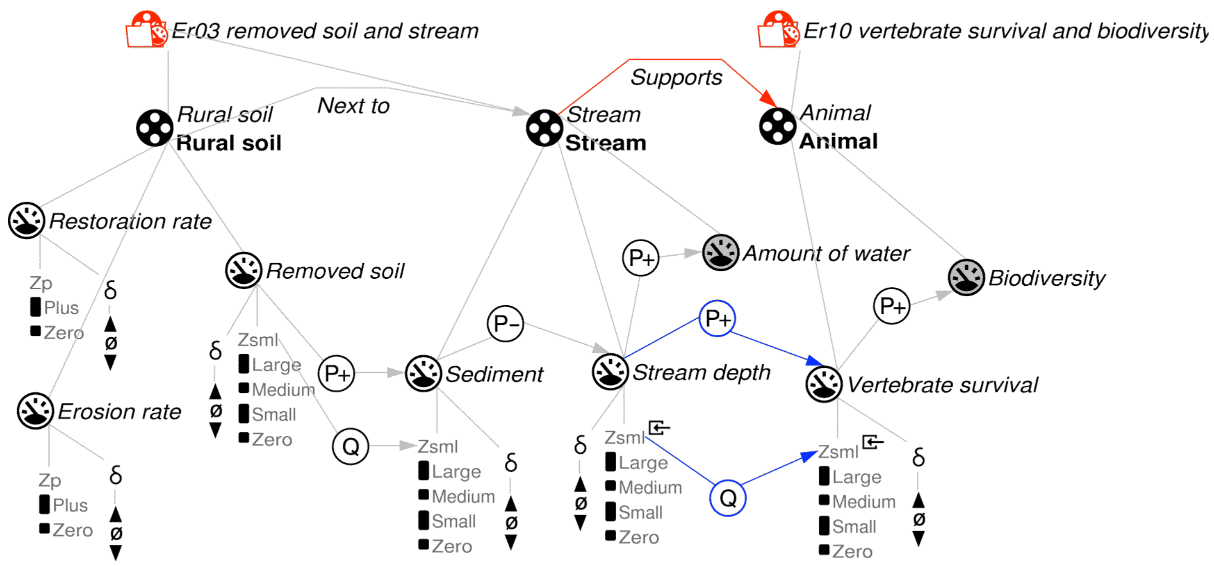


Figure ER.10. Static model fragment 'Stream and vertebrate survival'.

5.1.11 Soil fertility

Erosion influences soil fertility and eventually this influence propagates to agricultural uses of the land and affects the economy. The model fragment 'Soil fertility' captures the relations involving the quantities *Removed soil*, *Nutrient* and *Fertility*. Note that the concept of 'fertility' is broader than the concept of 'nutrients'. Making this distinction here is handy for further extensions of this submodel, which may include, for instance, the relation between organic matter and soil fertility. For the moment, the correspondence sets the values of *Fertility* according to those of *Nutrient*:

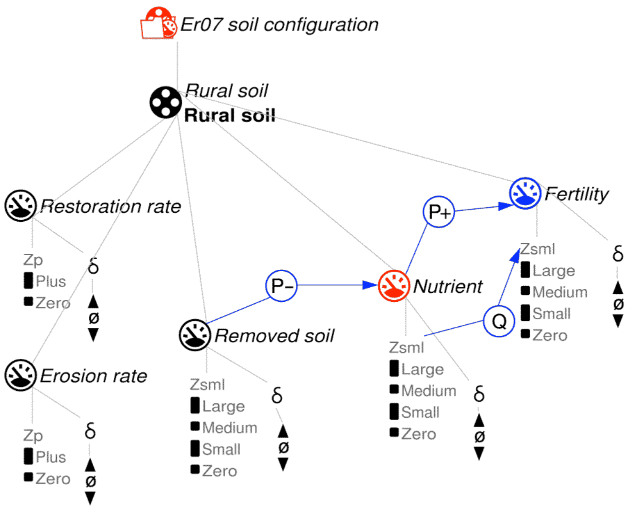


Figure ER.11. Static model fragment 'Soil fertility'.

5.1.12 Agriculture configuration

Agriculture, as an economic activity, is modelled as a relation involving the quantities *Resource inflow*, *Resource consumption*, *Production rate* and *Agricultural products*. This model fragment introduces the entity 'Agriculture' and these quantities:

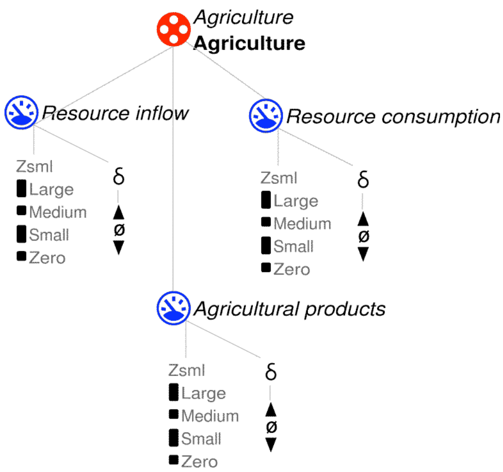


Figure ER.12. Static model fragment 'Agriculture configuration'.

5.1.13 Agriculture needs soil and water

Water and soil fertility are among the most important resources for agriculture. This knowledge is captured by the the model fragment ‘Agriculture needs fertility and water’. As in the Riacho Fundo (and in the Cerrado biome in general) soils tend to be poor of nutrients, the influence from *Fertility* is assumed to be preponderant on the resource inflow for agricultural production:

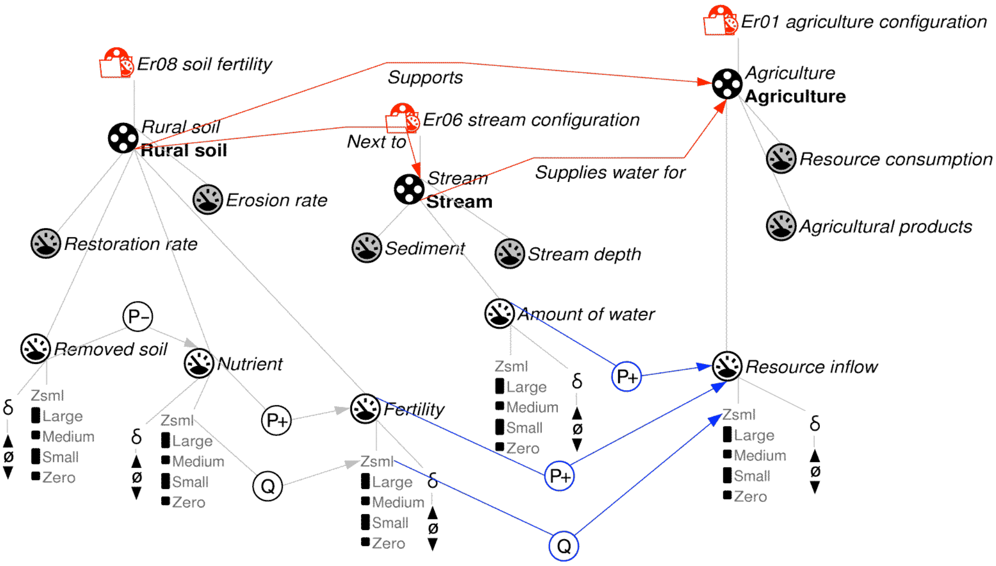


Figure ER.13. Static model fragment ‘Agriculture needs soil and water’.

5.1.14 Agricultural production process

Finally, the mechanism of agricultural production is represented in this model fragment:

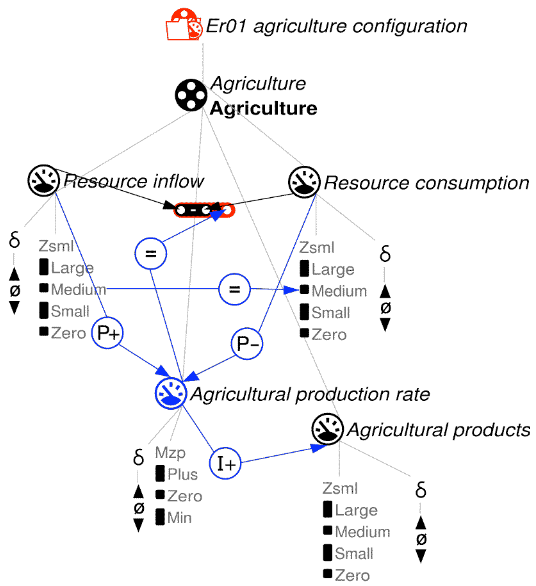


Figure ER.14. Process model fragment ‘Agricultural production process’.

As discussed before, three additional children model fragments were included in the library, stating that *Resource inflow* is equal, greater than and smaller than *Resource consumption*.

5.2 Scenarios and simulations

In its current version, the submodel Erosion has nine scenarios that support simulations of increasing complexity. Summaries of seven and details of two simulations are presented here. Finally, for better understanding the simulations, it may be useful to consult the causal model for the Erosion submodel, presented in section 5.2.6 (Figure ER.23).

5.2.1 Vegetation cover only

The simplest scenario deals only with the inequality between *Regeneration* and *Degradation* of vegetation. It introduces only four quantities in the simulation.

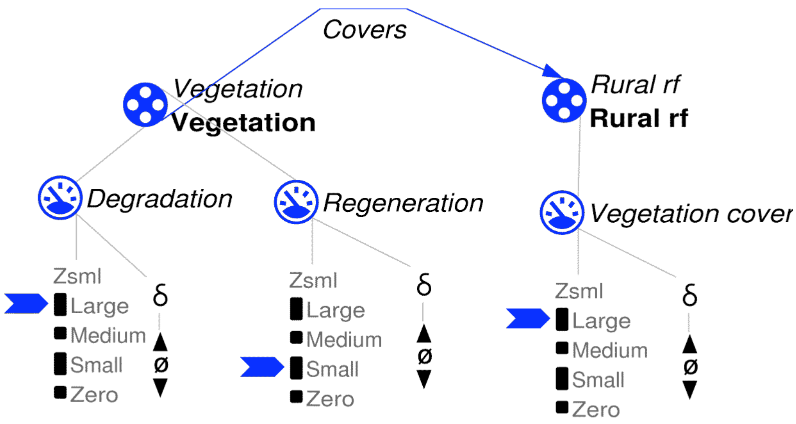


Figure ER.15. Initial scenario ‘Vegetation cover only’.

Scenario name	‘Vegetation cover only’
Full simulation	3 states
Initial states	[1]
End states	[3]
Relevant behaviour path	[1→2→3]
Behaviour description	The quantity *Regeneration* keeps the value <*Small*, *Minus*>, *Degradation* the value <*Large*, *Plus*>, and *Vegetation growth* the value <*Minus*, *Minus*> during the whole simulation. Accordingly, *Vegetation cover* starts with the value <*Large*, *Minus*> and, in state 3, it assumes the value <*Small*, *Minus*>.

Table ER.01. Simulation summary: initial scenario ‘Vegetation cover only’.

5.2.2 Vegetation cover and soil

The quantity *Removed soil* is introduced in this scenario, and as a consequence the simulation involves seven quantities.

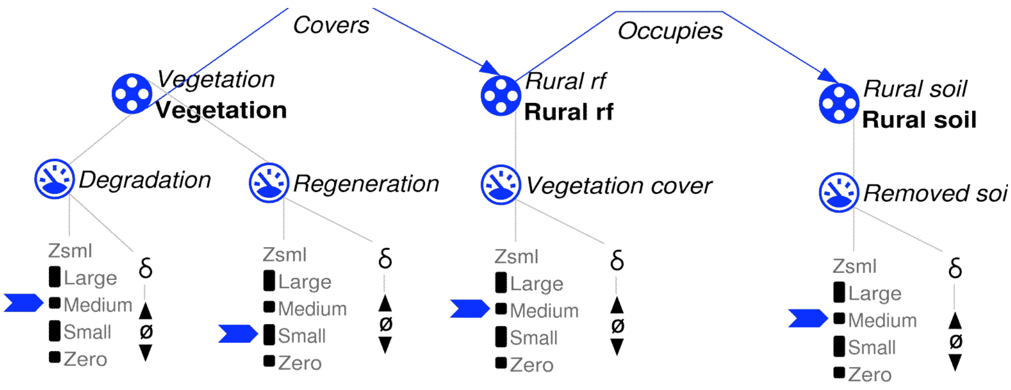


Figure ER.16. Initial scenario 'Vegetation cover and soil'.

Scenario name	'Vegetation cover and soil'
Full simulation	6 states
Initial states	[1, 2, 3]
End states	[4, 5]
Relevant behaviour path	[1→6→4]
Behaviour description	As in the previous simulation, *Regeneration* is smaller than *Degradation* so *Vegetation growth* has value <*Minus*, *Minus*> during the whole simulation. *Vegetation cover* starts with the value <*Medium*, *Minus*>, decreases to value <*Small*, *Minus*> in state 6 and keeps this value until the end state. As the initial equality between the soil related processes change, *Restoration rate* becomes smaller than *Erosion rate* and the quantity *Removed soil* starts increasing. It reaches the value <*Large*, *Minus*> in the end state.

Table ER.02. Simulation summary: initial scenario 'Vegetation cover and soil'.

5.2.3 Vegetation cover, soil and stream

This scenario introduces the entity 'Stream' and related quantities, so that the simulation involves 10 quantities.

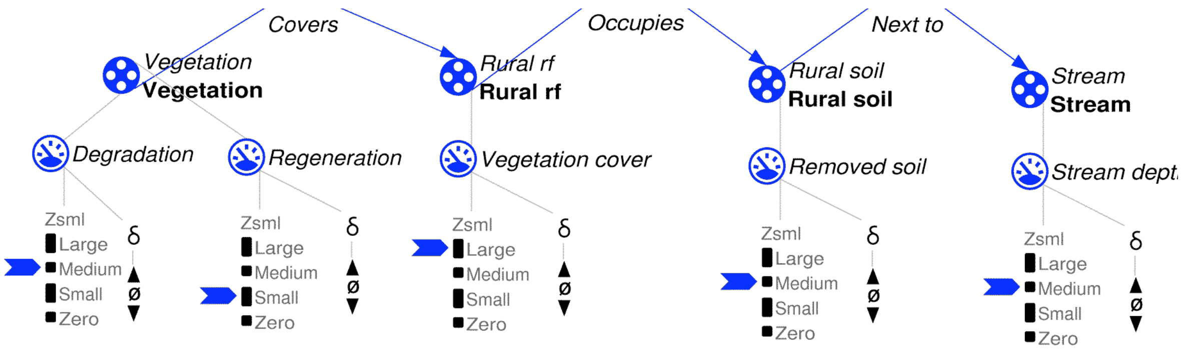


Figure ER.17. Initial scenario ‘Vegetation cover, soil and stream’.

Scenario name	‘Vegetation cover, soil and stream’
Full simulation	10 states
Initial states	[1, 2, 3]
End states	[9, 10]
Relevant behaviour path	[1→6→4→8→9]
Behaviour description	As in the previous simulations, *Regeneration* is smaller than *Degradation* so *Vegetation cover* starts with the value <*Large*, *Minus*>, decreases to value <*Medium*, *Minus* > in state 8 and to <*Small*, *Minus* > in the end state. As the initial equality between the soil related processes change, *Removed soil* starts stable, in state 6 it goes to the value <*Large*, *Positive*> and keeps this value until the end state. The quantity *Sediment* follows the same behaviour as *Removed soil*, and *Stream depth* changes to <*Medium*, *Minus*> in state 6, moves to <*Small*, *Minus*> in state 4 and keeps this value until the end state. The *Amount of water* in the stream follows the same behaviour.

Table ER.03. Simulation summary: initial scenario ‘Vegetation cover, soil and stream’.

5.2.4 Vegetation cover, soil, stream and biodiversity

This scenario introduces the entity ‘Animal’ and related quantities, so that the simulation involves 12 quantities. The system behaviour is more complex, and it is worth to present some details of this simulation. The figure below shows the initial scenario ‘Vegetation cover, soil, stream and biodiversity:

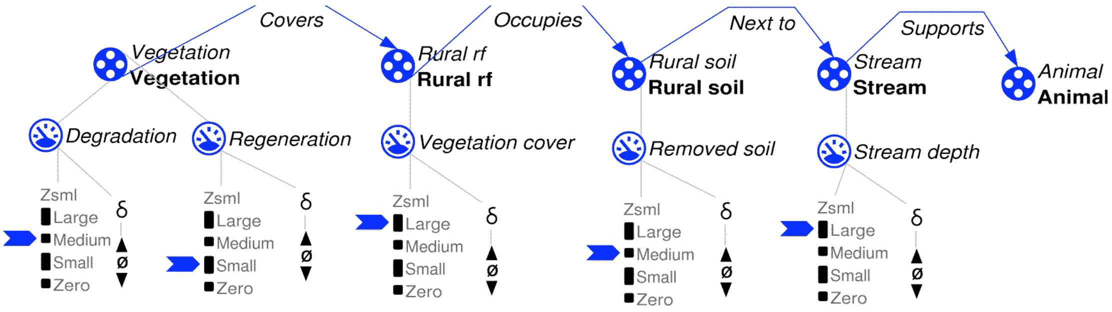
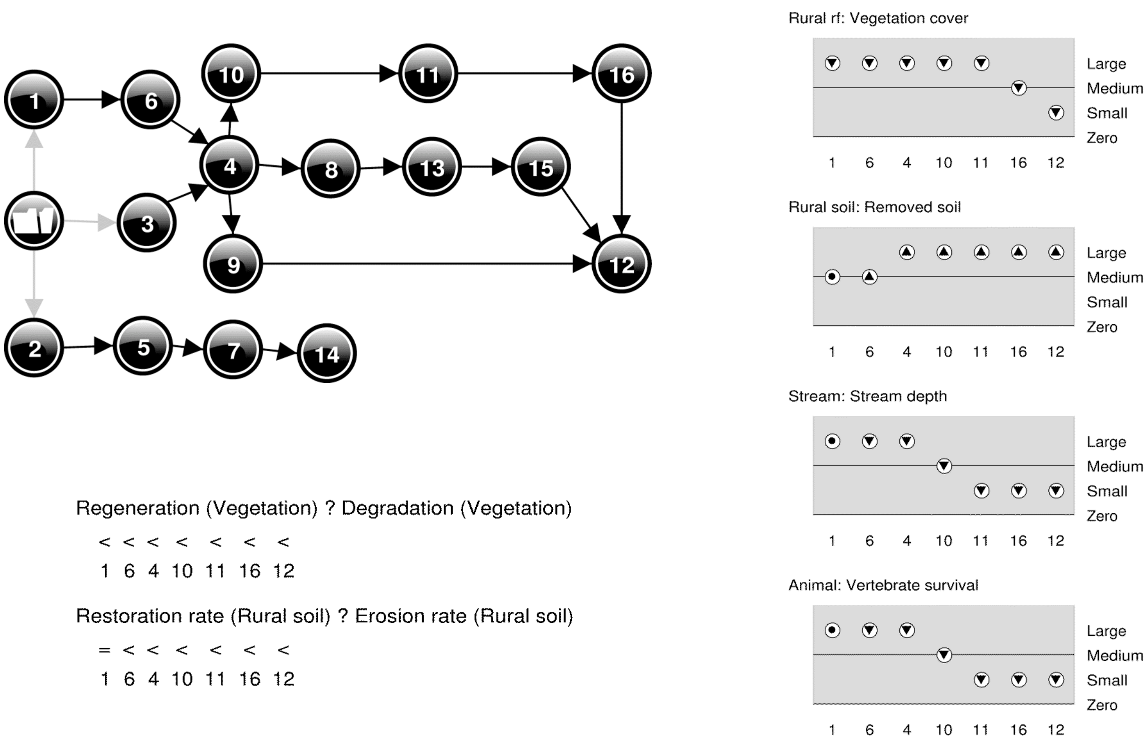


Figure ER.18. Initial scenario ‘Vegetation cover, soil, stream and biodiversity’.

The simulation with this scenario starts with three initial states, and the full simulation produces 16 states, with two end states, [14, 12]. Figure ER.19a presents the behaviour graph of this simulation:



(a) (b)

Figure ER.19 (a) Behaviour graph of the simulation produced by the scenario ‘Vegetation cover, soil, stream and biodiversity’ and equation history diagram in a selected behaviour path. (b) Value history diagram of selected quantities in a selected behaviour path.

In order to see the consequences of the degradation of the vegetation cover on biodiversity, we selected the behaviour path [1→6→4→10→11→16→12] to explore. Figure ER.19b above shows the value history diagrams of the quantities *Vegetation cover*, *Removed soil*, *Stream depth* and *Vertebrate survival*. The behaviour of these quantities can be explained as follows: as *Degradation* is always bigger than *Regeneration* (see Figure ER.19a) *Vegetation cover* is decreasing in the whole simulation. As a consequence, it changes que equality between *Recovery rate* and

Erosion rate and causes the quantity *Removed Soil* to increase. Accordingly, this is transported to the stream, so that the amount of sediments increase and causes the quantity *Stream depth* to decrease. The causal chain presented in the model fragment 'Stream and vertebrate survival' (see section 5.1.10) eventually causes the quantity *Vertebrate survival* to decrease, resulting in loss of biodiversity. A clear picture of the whole causal chain established in this submodel is presented below, in Figure ER.23.

5.2.5 Vegetation cover, soil, stream and agriculture

The next scenario explores the consequences of changes in the vegetation cover for the agricultural production. Leaving aside issues related to biodiversity, the simulation of this scenario involves 16 quantities. Figure ER.20 presents the initial scenario 'Vegetation cover, soil, stream and agriculture':

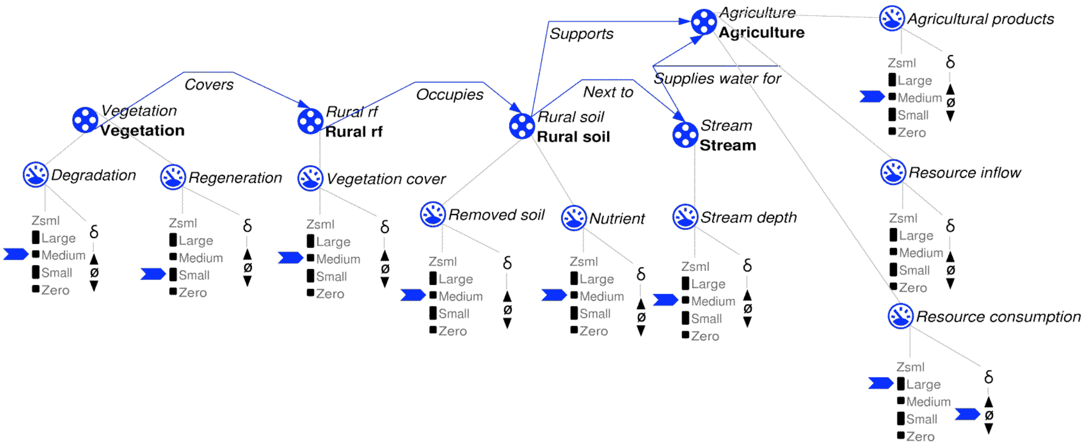


Figure ER.20. Initial scenario 'Vegetation cover, soil, stream and agriculture'.

Scenario name	'Vegetation cover, soil, stream and agriculture'
Full simulation	12 states
Initial states	[1, 2, 3]
End states	[4, 12]
Relevant behaviour path	[2→5→9→11→12]
Behaviour description	Although *Vegetation cover* decreases, *Removed soil* also decreases in this behaviour path and keeps the value <*Small*, *Minus*> until to the end state. The quantity *Fertility* increases influencing the agricultural production. *Resource inflow* moves from <*Medium*, *Plus*> in state 2 to <*Large*, *Plus*> in state 5 and keeps this value until the end state. As a consequence, it changes the behaviour of the quantity *Agricultural products*: this quantity started the simulation with the value <*Medium*, *Minus*> in state 2, moves down to <*Small*, *Minus*> in state 5, stabilizes in state 9 and start increasing in state 11. In state 12, the final value of *Agricultural products* is <*Large*, *Plus*>.

Table ER.04. Simulation summary: initial scenario 'Vegetation cover, soil, stream and agriculture'.

5.2.6 Vegetation cover, soil, stream, agriculture and biodiversity

This is the more complete scenario of the submodel Erosion. It addresses all the phenomena mentioned in the previous scenarios and involves 18 quantities in the simulation. Figure ER.21 shows the system structure and the initial values of relevant quantities for starting the simulation:

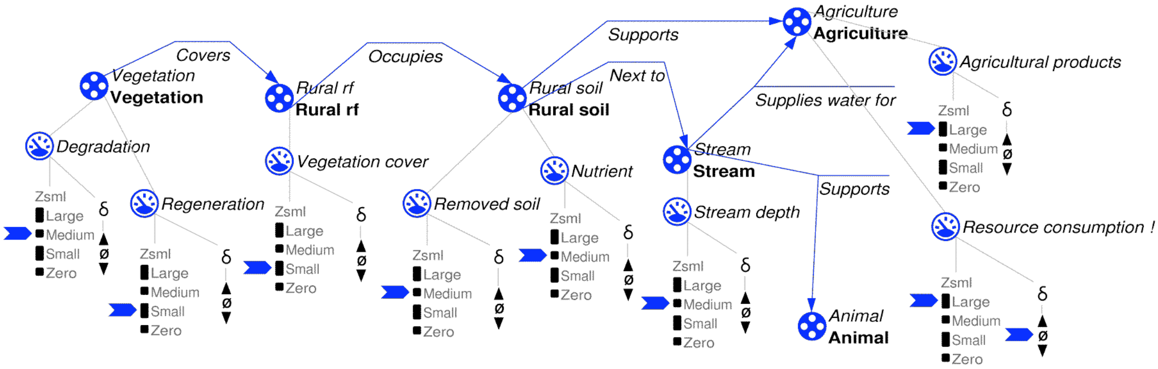


Figure ER.21. Initial scenario 'Vegetation cover, soil, stream, agriculture and biodiversity'.

This scenario produces a simulation that starts with three initial states, and has the total of 18 states. There are two end states, [11, 12]. The behaviour graph of this simulation is presented in the following figure:

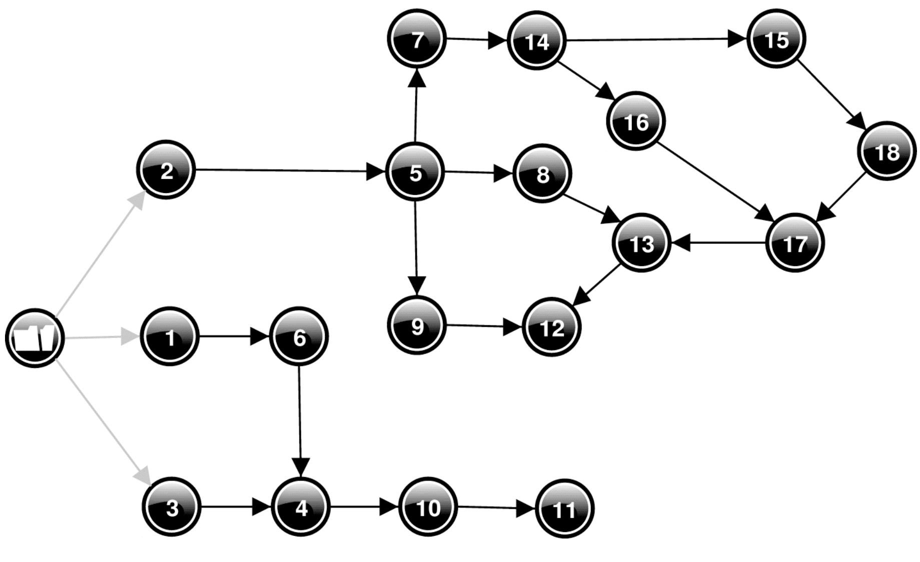


Figure ER.22. Behaviour graph produced in a simulation starting with the initial scenario 'Vegetation cover, soil, stream, agriculture and biodiversity'.

The causal model, as it appears in state 2 of the simulation, combines 16 ative model fragments and is shown in Figure ER.23:

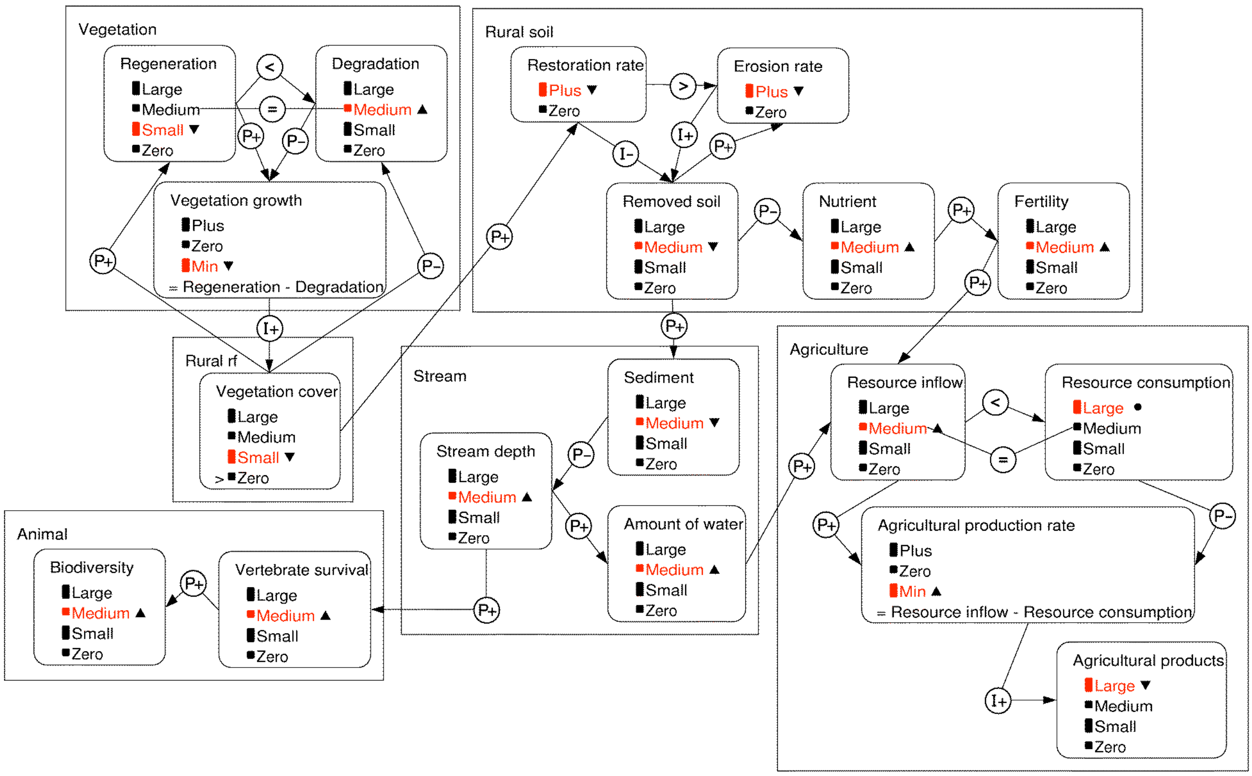


Figure ER.23: Causal model in state 2 of the simulation that starts with the scenario ‘Vegetation cover, soil, stream, agriculture and biodiversity’.

In order to explore this simulation and to understand how the system behaviour comes about, following behaviour path was selected: [2→5→7→14→16→17→13→12]. The values of relevant quantities are presented in the Figure ER.24 below:

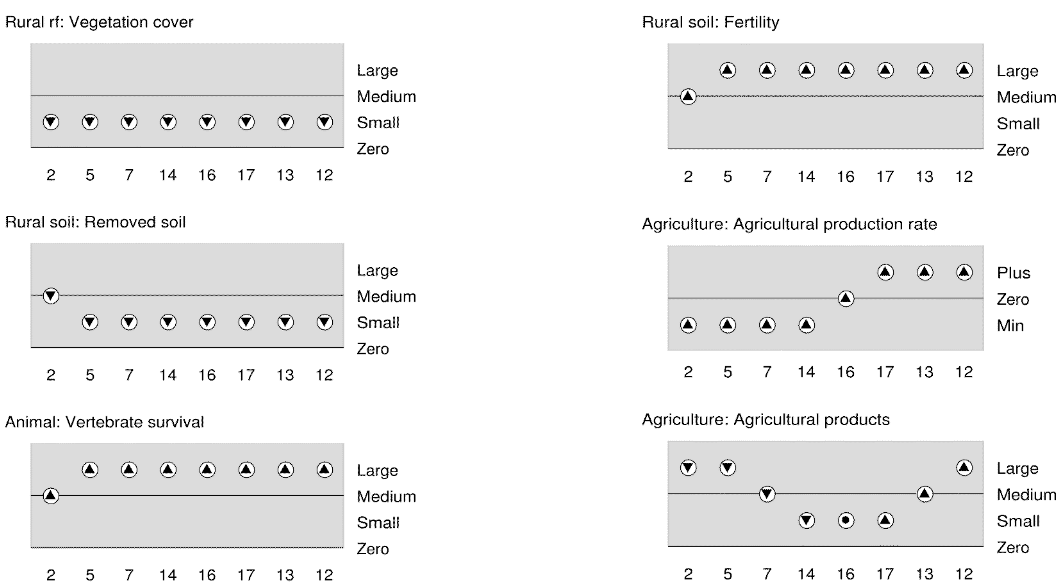


Figure ER.24 Value history diagram of selected quantities in a selected behaviour path.

In this behaviour path, *Vegetation cover* is decreasing because, as in the previous simulations, *Degradation* is greater than *Regeneration*. Via the feedback loops, the decrease of *Vegetation cover* causes *Degradation* the become even higher and *Regeneration* smaller. Changes in *Vegetation cover* causes *Restoration rate* to decrease, but this quantity is still smaller than *Erosion rate*, so *Removed soil* decreases. The latter quantity influences both *Sediment* and *Nutrient*. The effects on *Sediment* propagate to *Stream depth*, and from this quantity to *Vertebrate survival* and *Biodiversity*. Changes in *Nutrient* propagate to *Fertility*, which in turn affect the *Resource inflow* for the agricultural production. The balance between *Resource inflow* and *Resource consumption* only change in state 16, when they become equal, and from that state onwards, the former becomes bigger that the latter, causing the quantity *Agricultural production rate* to change from the value *Minus* to *Zero* and then to *Plus*. All these changes eventually cause the amount of *Agricultural products* to exhibit an interesting behaviour: started the simulation with the value *Large*, but decreasing; go to S*mall* in states 14, 16 and 17, and increase up to *large* again.

Comparing the behavior paths shown in this simulation to those presented in sections 5.2.4 and 5.2.5, it becomes clear that this model does not establish a strong link between degradation of the vegetation cover and soil removal due to erosion, loss of biodiversity and reduction in agricultural production. Although such a link is part of the commonsense knowledge about how humans are changing the environenment, it is possible to have these contradictory situations, at least for a certain period, given the understanding of the process of soil restoration discussed in section 5.1.4 and the way the soil processes were modelled. In fact, this is what is happening in the Riacho Fundo basin and many other places. However, is this a sustainable sitiuation? Probably no, as other factors beside the disponibility of nutrients are needed to keep the soil as productive.

Additional details about this simulation can be found in the Annex (section 9).

6 Follow up

Although this is the final document about the Riacho Fundo model for the project Naturnet-Redime, the work is not finished yet. Of course, apart from the fact that there are always opportunities for improving any model, both from the representational and from the functional points of view, this model will be integrated to the Library of model fragments that is being developed in Task 6.7 and will become didactic material within curricula for learning about sustainability (Task 6.8). In this section some follow up to the work described in this Deliverable is briefly discussed.

It is not an easy task to integrate three submodels and produce a large model, with 24 entities, 11 processes and 45 quantities, organized in 65 model fragments, in order to produce 30 structurally different simulations (changes in initial values of the quantities using the same scenario are not included). This result was obtained by careful design of entities and configurations, that is, of the structure of the system being modelled.

In the Riacho Fundo model, the entities are associated to other entities by means of clearly defined configurations, so that each piece of the system structure is unique. This way, it is possible to fully explore each submodel within the common library of model fragments and scenarios, as if it was separate from the other submodels. This Deliverable is full of examples of how independent the submodels are. In this sense, the integrated Riacho Fundo model is running correctly, and the stakeholders may benefit from the wide range of simulations available.

However, an interesting research goal is how to combine elements of different submodels to create new pieces of system structure, so that it will be possible to run simulations and inspect simultaneously problems in different areas of the Riacho Fundo basin. For example, erosion is a theme addressed both in the urban and in the rural areas by the Urban drainage and the Erosion submodels, and the stakeholders would like to inspect the general effects of erosion on the basin.

Some tentatives were done so far, with promissing results. For instance, the current library of the Riacho Fundo model was extended with four additional model fragments created to define the following configurations between entities of different submodels:

(a) ‘Urban rf *connected to* Semi urban rf’;

(b) ‘Urban rf *connected to* Rural rf’;

(c) ‘Semi urban rf *connected to* Rural rf’; and

(d) ‘Rural rf *connected to* Urban rf *connected to* Semi urban rf’

For instance, the following figures, produced by Garp3, represent new structures created in simulations that integrate already implemented submodels scenarios:

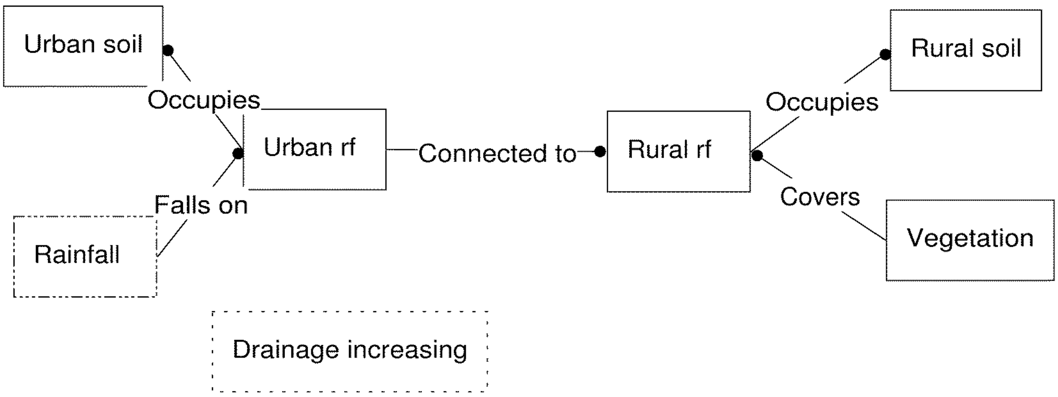


Figure FU. 01 Entities and configurations created by the integration of scenarios from the submodels Urban drainage and Erosion.

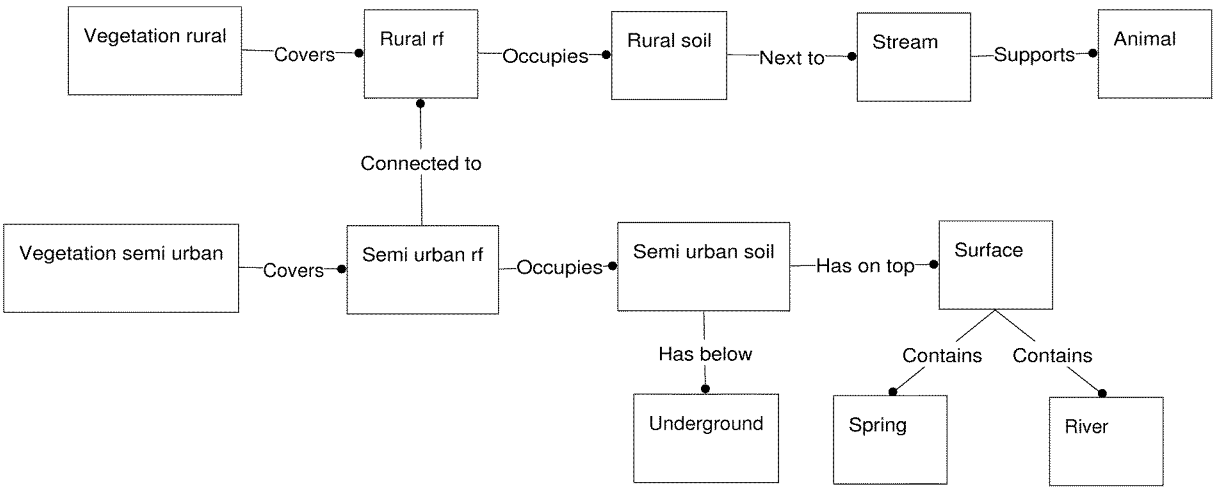


Figure FU. 02 Entities and configurations created by the integration of scenarios from the submodels Springs and Erosion.

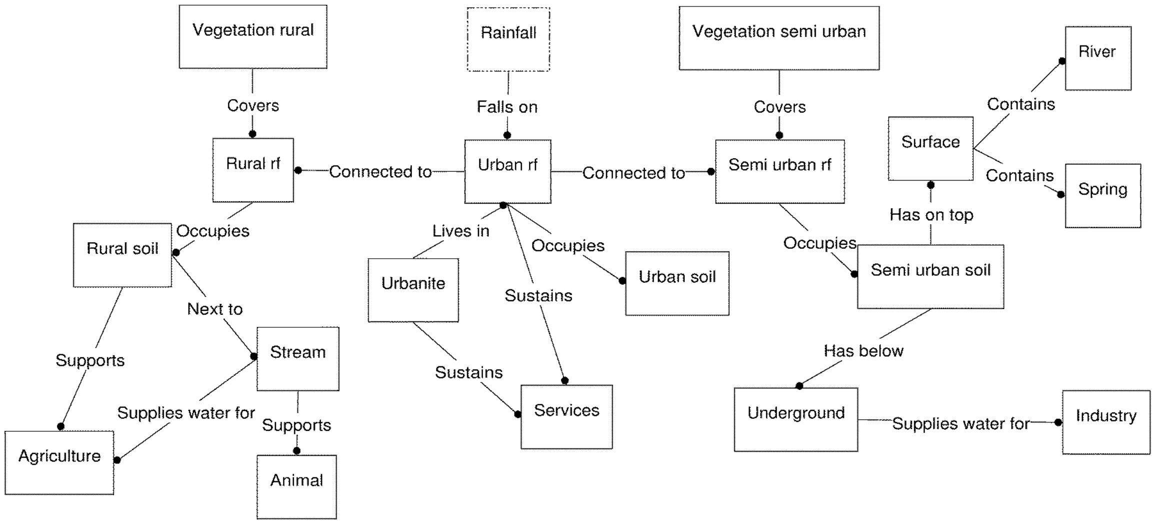


Figure FU. 03 Entities and configurations created by the integration of scenarios from the submodels Urban drainage, Springs and Erosion.

However, the resulting simulations are too complex, as Garp3 tries all the possible combinations of quantity values included in the simulation. This way, when simple simulations that produce few states are combined, the new simulations produce much more states than the simple addition of states produced by the separate models.

Tentatives for tackling these combinatorial explosions are currently being undertaken. The solution includes (a) reducing the ambiguity in the knowledge representation; (b) the development of common model fragments that can be used in different submodels; and (c) the refinement of concepts that are common to different systems (for example, to find a common representation for any type of economic activity – agriculture, industry and services). As mentioned above, the results obtained so far are promissing and should become applicable to the library of model fragments that is being developed in Task 6.7. These results will certainly become the basis for future projects to be developed as follow up of the Naturnet – Redime project.

7 Discussion and conclusions

The simulation model about the Riacho Fundo case study and the associated learning materials presented in this document follow the guidelines defined in the Deliverable D6.4.1 (Salles and Caldas, 2006a), and refine the prototype presented in the Milestone M6.4 (Salles and Caldas, 2006b).

The Riacho Fundo model integrates three submodels, Urban drainage, Springs and Erosion. It encodes knowledge about changes in a river basin from its natural conditions into rural, semi urban and urban areas. Accordingly, a wide range of problems is explored in the integrated mode, including: deforestation, floods, garbage transportation, erosion in urban and in rural soil, human well being, aggregation of soil particles, infiltration of water to the underground, rivers, springs and underground water, agricultural and industrial production, loss of fertility, biodiversity.

Each submodel was supposed to provide answers to a question formulated in the beginnig of the sections 3, 4 and 5. Here the answers for those questions are discussed.

Urban drainage: The Urban drainage submodel provides answers for the question formulated in the beginning of section 3 as follows: a good infrastructure for the drainage system in urban areas reduces the effects of the erosion process, reduces the damage caused by flooded areas and garbage transportation. The submodel implements two perspectives, with and without control on the water runoff originated from the rainfall. This way, the learner can compare simulation results and maybe have insights about the sustainability of urban areas. Finally, an implemented drainage system increases the human well being.

Springs: The Springs submodel provides answers to the question formulated in the beginning of section 4 as follows: changes in the soil features due to urbanization pressures reduce the amount of water in springs and streams and may reduce the industrial production in the basin. Controlling the urbanization pressure and keeping the possibility of water infiltration in the soil is a key issue for sustainability.

Erosion: The Erosion submodel provides answers to the question formulated in section 5 as follows: deforestation, soil protection and erosion influence water resources and soil fertility, elements that are input for the agricultural production. The removed soil affects the conditions of water bodies, which in turn influences the survival of animals and biodiversity. Soil protection may increase the inflow of resources for the agricultural production and keep ecosystem services working.

The Riacho Fundo model was developed for support stakeholders in improving their understanding of problems related to sustainable development. Beside the lessons to be learned with the answers provided by the submodels to questions discussed above, there is a wealth of conceptual knowledge available in the model fragments and in simulations created by the model that can be useful in educational contexts. Some of these possible applications are discussed below:

Firstly, each model fragment can be seen as a stand alone didactic material (see the ‘one concept, one model fragment rule’ discussed in Salles and Bredeweg, 1997). The description of the infiltration process, in the submodel Springs (section 4.1.5), illustrates this point. A single model fragment (Figure SP. 05) captures complex knowledge about:

(a) structurally related regions of the soil (the surface is on the top of the soil and the undergound is located below the top of the soil);

(b) the effects of infiltration on the quantities *Amount of water* present in two different locations (the amount of water increases at the underground and decreases at the surface);

(c) control mechanisms working as feedback loops from the amount of water on the *Infiltration rate* (in fact two different mechanisms, as the rate causes the water on the surface to drecrease, and the underground water to increase, with the same same final effect, that is to reduce the rate);

(d) the condition for the process to be active (amount of water at the surface greater than zero).

Secondly, the compositional modelling approach (Falkenhainer and Forbus, 1991) used to build the models has proven to be a powerful way of integrating knowledge represented as ‘simple’ stand-alone pieces of models (model fragments) in order to build more complex representations of the system (simulation models and simulations). In all the submodels, simulations were presented in an incremental way, starting with less complex problems and gradually including more entities, quantities and model fragments. For example, simulations of the Erosion submodel (section 5.2), involved initially 2 entities and 4 quantities (section 5.2.1); then, 3 entities and 7 quantities (section 5.2.2); 4 entities and 10 quantities (section 5.2.3); 5 entities and 12 quantities (section 5.2.4) or 16 quantities (section 5.2.5); and finally, 6 entities and 18 quantities (section 5.2.6). The potential of qualitative reasoning models for carefully designed curricula to tackle complex domains, as sustainability, is enormous (see, for example, Bredeweg and Forbus, 2003).

Of course, a number of technical problems had to be addressed in order to obtain this large model, that comprises, in its current stage of implementation, 24 entities, 11 processes and 45 quantities, organized in 65 model fragments, in order to produce 30 simulations. As it occurs in the development of any model, the Riacho Fundo model is not finished, and probably there will be always some points to be improved. Besides ongoing work focusing on improving the integration of submodels in the Riacho Fundo model and on the integration of models produced by the Naturnet project case studies, an important issue to be addressed is the evaluation of the Riacho Fundo model. Although it has been evaluated by experts, evaluation by stakeholders is considered to be essential and will be done in the near future.

Concluding, we believe the Riacho Fundo model will meet the objetives defined in the beginning of this modelling enterprise: it will improve understanding of environmental systems and problems that may affect sustainability in the basin; it will become a powerful tool to demonstrate the effects of human actions, both positively and negatively influencing different aspects of the Riacho Fundo basin system; it will be useful to support communication between stakeholders, policy makers, modellers and the public; and last, but not least, it will support stakeholders in learning and becoming active on issues related to sustainability.

8 References

Bredeweg, B. and Forbus, K. (2003) Qualitative Modeling and Education. *AI Magazine*, Volume 24, Number 4, pages 35-46.

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Salles, P. and Bredeweg, B. (1997) Building Qualitative Models in Ecology. In Ironi, L. (ed.) *Proceedings of the 11th. International Workshop on Qualitative Reasoning (QR'97)*. Instituto di Analisi Numerica C.N.R., Pubblicazioni no. 1036 , Pavia, Italy.

9 Annex

This Annex presents details of the full simulations with the more complex scenarios of the three submodels (Urban drainage, Springs and Erosion).

9.1 Urban drainage submodel

For details about this simulation, including the scenario ‘Drainage increasing, economy, well being and soil’, the behaviour graph and the causal model, see section 3.2.5

9.1.1 Equation history

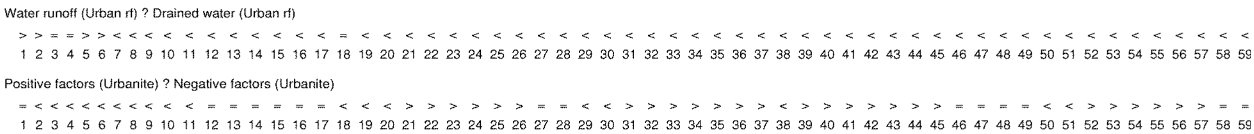

Figure A.01. Equation history of all the states produced in the simulation of the scenario ‘‘Drainage increasing, economy, well being and soil’.

9.1.2 Value history diagrams

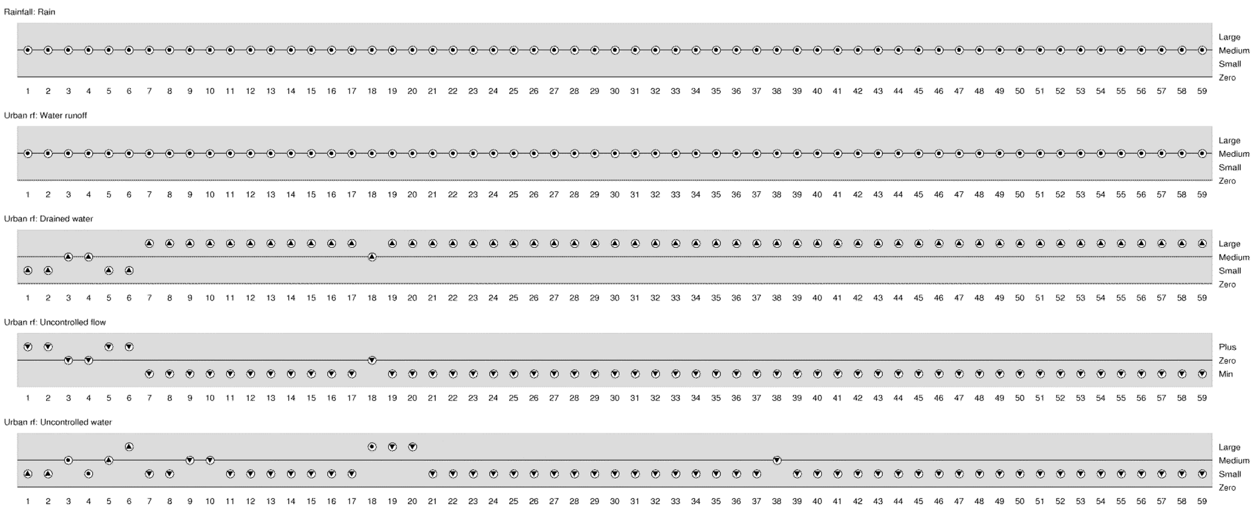

Figure A.02. Value history diagrams of all quantities in all the states produced in the simulation of the scenario ‘‘Drainage increasing, economy, well being and soil’ – part 1.

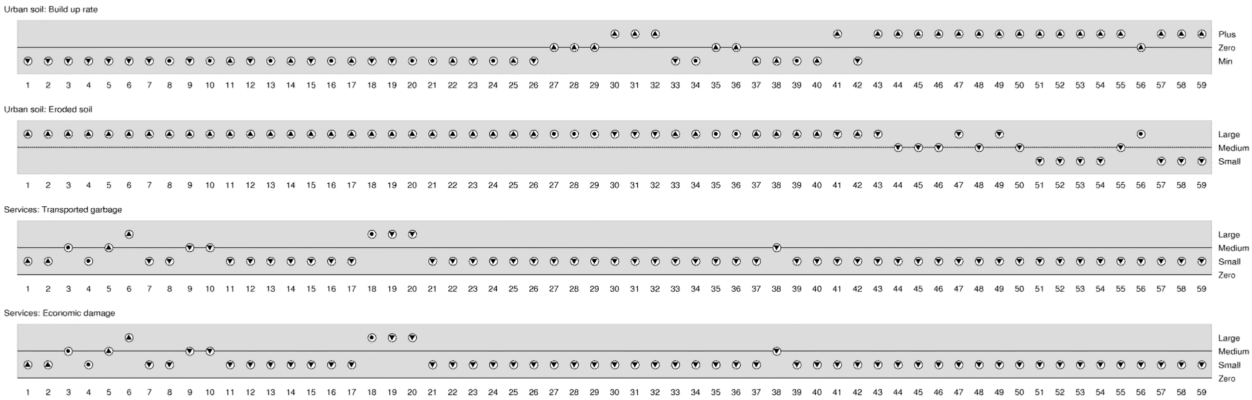

Figure A.03. Value history diagrams of all quantities in all the states produced in the simulation of the scenario ‘‘Drainage increasing, economy, well being and soil’ – part 2.

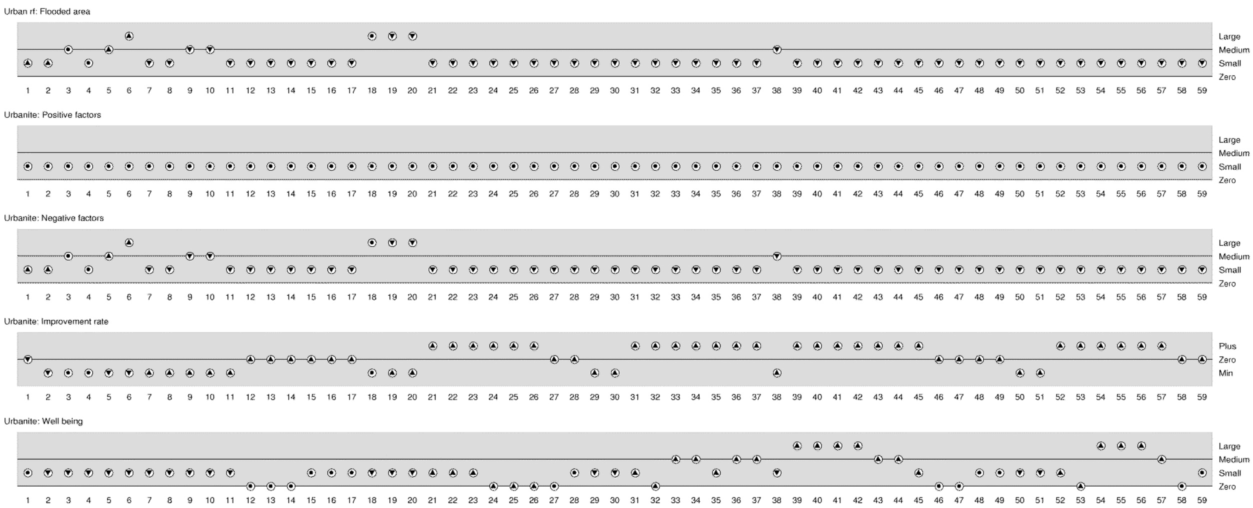

Figure A.04. Value history diagrams of all quantities in all the states produced in the simulation of the scenario ‘‘Drainage increasing, economy, well being and soil’ – part 3.

9.2 *Springs submodel*

For details about this simulation, including the scenario ‘Semi-urban cover, infiltration, spring, river and industry’, the behaviour graph and the causal model, see section 4.2.6.

9.2.1 Equation history

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
Urbanization pressure (Semi urban rf) ? Biological pressure (Vegetation)	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
Resource inflow (Industry) ? Resource consumption (Industry)	<	<	<	<	<	<	<	<	=	=	<	=	=	=	=	=	<	=	<	<	<	>	>	>	>	>	>	>	>	>	>	>	>	>	>	>	>
Amount of water (Surface) ? Zero	>	>	>	>	>	>	>	>	>	>	>	>	>	=	>	=	=	>	>	=	=	>	>	>	>	>	>	>	>	=	=	=	=	>	>	>	=

Figure A.05. Equation history diagram of all the states produced in the simulation of the scenario ‘Semi-urban cover, infiltration, spring, river and industry’.

9.2.2 Value history diagrams

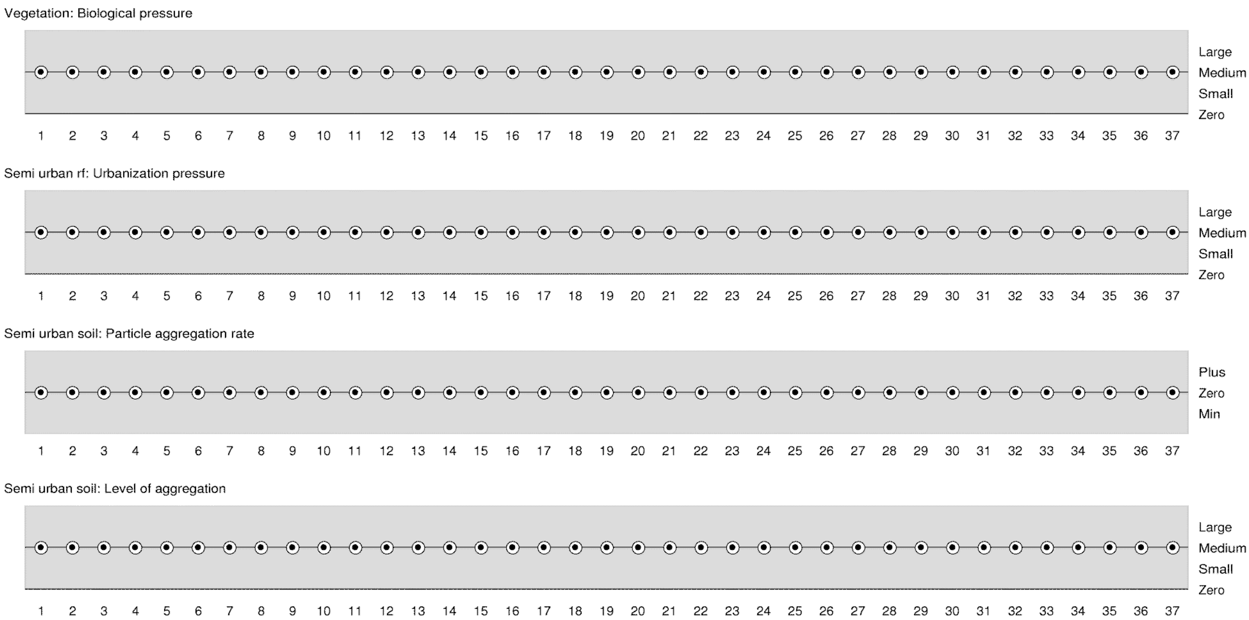

Figure A.06. Value history diagrams of all quantities in all the states produced in the simulation of the scenario ‘Semi-urban cover, infiltration, spring, river and industry’– part 1.

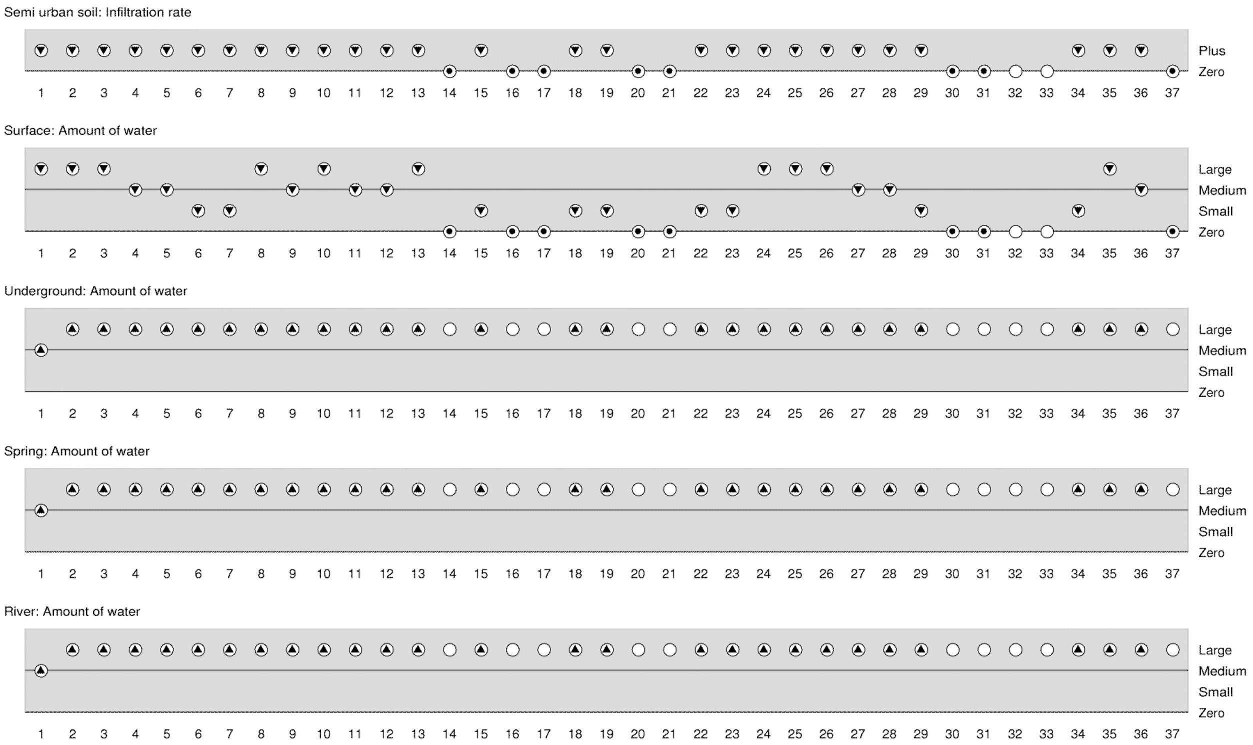

Figure A.07. Value history diagrams of all quantities in all the states produced in the simulation of the scenario 'Semi-urban cover, infiltration, spring, river and industry'– part 2.

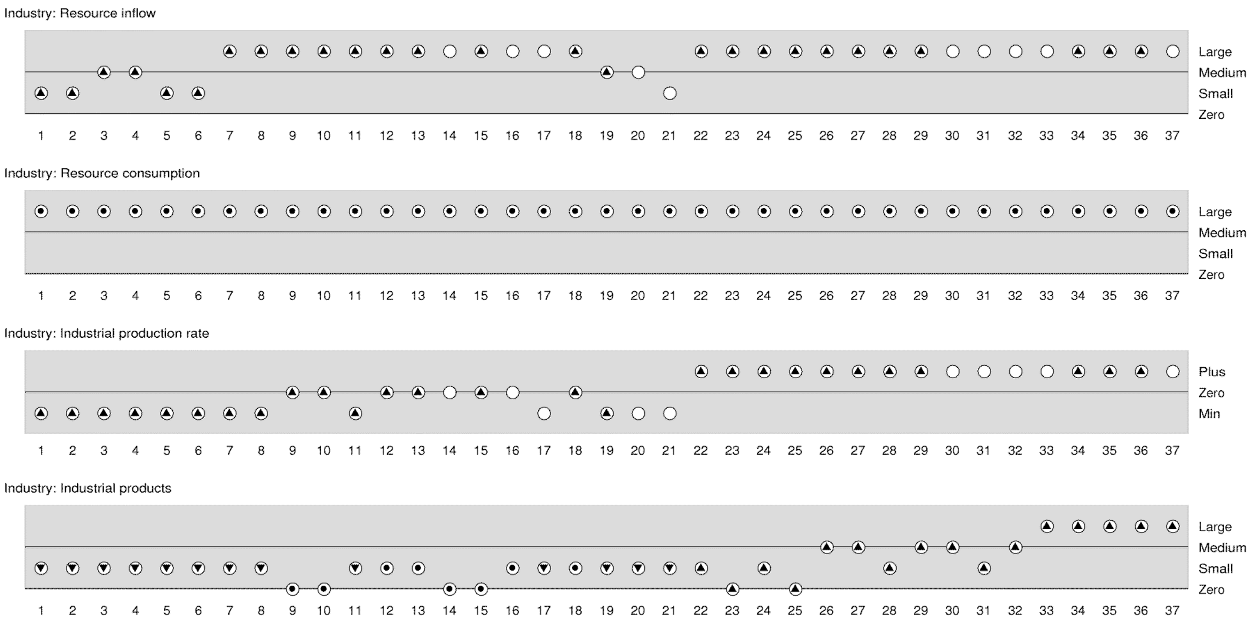

Figure A.08. Value history diagrams of all quantities in all the states produced in the simulation of the scenario 'Semi-urban cover, infiltration, spring, river and industry'– part 3.

9.3 Erosion submodel

For details about this simulation, including the scenario 'Vegetation cover, soil, stream, agriculture and biodiversity', the behaviour graph and the causal model, see section 5.2.6.

9.3.1 Equation history

Regeneration (Vegetation) ? Degradation (Vegetation)

<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Vegetation cover (Rural rf) ? Zero

>	>	>	>	>	>	>	>	>	>	>	>	>	>	>	>	>	>
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Restoration rate (Rural soil) ? Erosion rate (Rural soil)

=	>	<	<	>	<	>	>	>	<	<	>	>	>	>	>	>	>
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Resource inflow (Agriculture) ? Resource consumption (Agriculture)

<	<	<	<	<	<	<	=	=	<	<	>	>	<	=	=	>	>
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Figure A.09. Equation history diagram of all the states produced in the simulation of the scenario 'Vegetation cover, soil, stream, agriculture and biodiversity'.

9.3.2 Value history diagrams

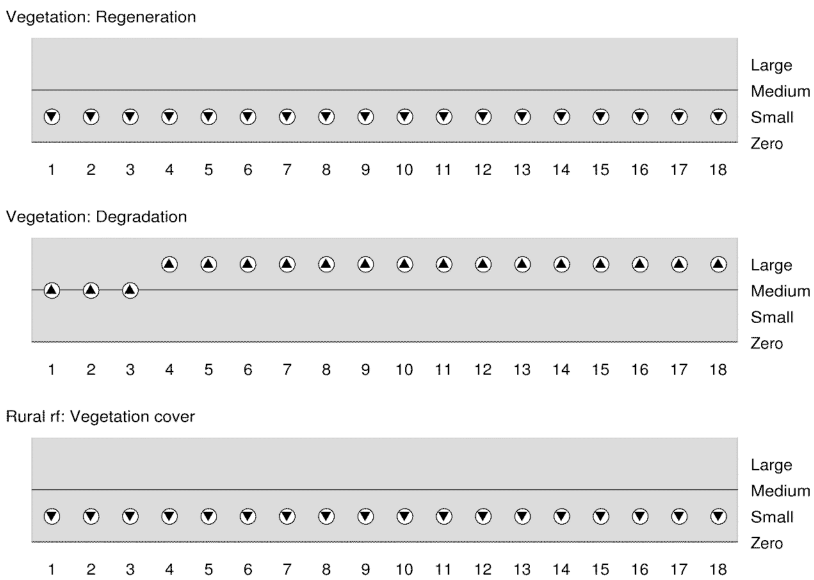

Figure A.10. Value history diagrams of all quantities in all the states produced in the simulation of the scenario 'Vegetation cover, soil, stream, agriculture and biodiversity'. – part 1.

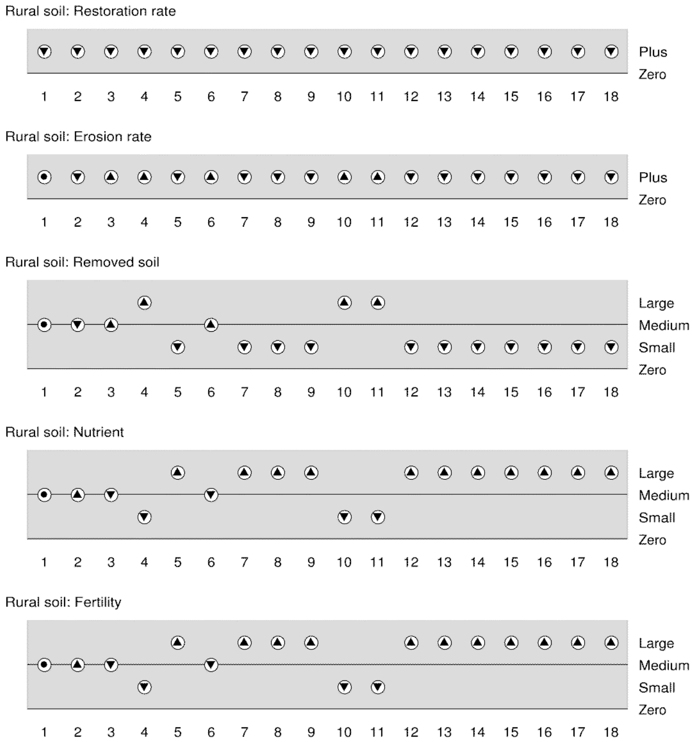

Figure A.11. Value history diagrams of all quantities in all the states produced in the simulation of the scenario 'Vegetation cover, soil, stream, agriculture and biodiversity'. – part 2.

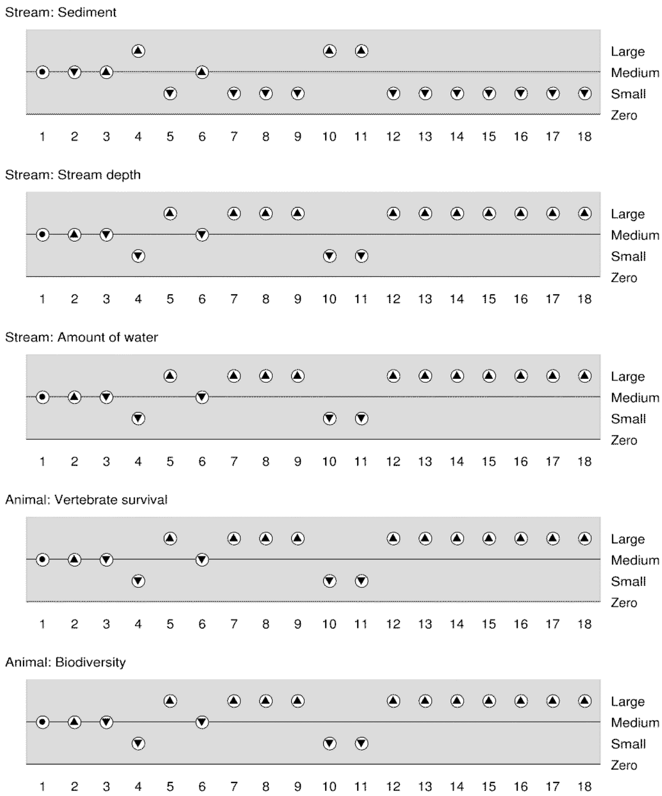

Figure A.12. Value history diagrams of all quantities in all the states produced in the simulation of the scenario 'Vegetation cover, soil, stream, agriculture and biodiversity'. – part 3.

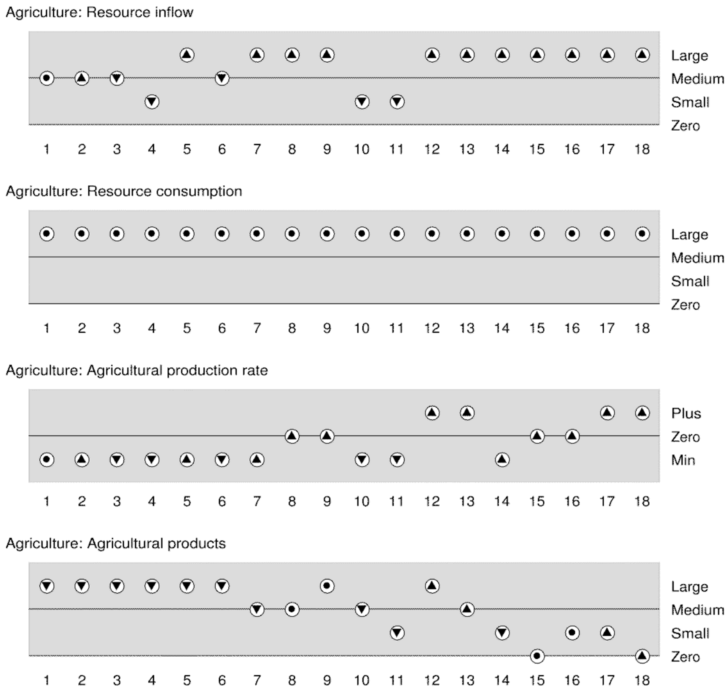

Figure A.13. Value history diagrams of all quantities in all the states produced in the simulation of the scenario ‘Vegetation cover, soil, stream, agriculture and biodiversity’. – part 4.