Modelling sustainability in the Riacho Fundo water basin (Brasília, Brazil)

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Abstract

This paper explores the use of assumptions to build multiple models about sustainable development in a compositional way. It presents a model aiming at supporting stakeholders to improve their understanding about a water basin system under the pressure of changes in land use. Domain knowledge is approached from three perspectives: urban, semi-urban and rural. Simulations explore sustainability issues related to (a) the effects of urban drainage systems; (b) the dynamics of erosion and water infiltration in the soil; and (c) the effects of vegetation cover on soil and water conditions and agricultural production. The paper discusses the use of modelling primitives to define and implement perspectives based only in conceptual knowledge to approach ill-defined domains as sustainability.

1. Introduction

This paper describes the use of assumptions (Falkenhainer and Forbus, 1991) to define perspectives for organizing knowledge in a qualitative model about sustainability of the Riacho Fundo basin (Brasília, Brazil). The model was designed to support stakeholders and decision makers to improve their understanding about the complex problems they have to deal with, and is being developed in one of NaturNet–Redime project (www.naturnet.org) case studies. The work described here aims at answering the following research questions: dealing with a large body of domain knowledge, (a) how to organize knowledge encoded in a library of model fragments in order to create sets of simulation models each addressing a class of sustainability issues in the Riacho Fundo basin? and (b) how to optimize the use of Garp3's representational apparatus and algorithm (Bredeweg *et al*. 2006) to create multiple models as mentioned in (a)?

The use of modelling assumptions to define perspectives for reasoning with multiple models about physical systems is a long standing problem in Qualitative Reasoning. The goal of this paper is to discuss problems and solutions of perspective-taking using only conceptual knowledge about sustainability – which perspectives to take, how to represent them and how to explore modelling primitives to implement assumptions. The paper is organized as follows: in section 2, we briefly discuss relevant aspects of sustainability in the Riacho Fundo basin. Next, in section 3, fundamental aspects of QR theory and some details of Garp3 are presented. The implementation of three perspectives taken to sustainability is described in section 4, and in section 5 selected simulations are used to illustrate the model results. The implementation of assumptions is discussed in section 6. Finally, the paper ends with references to ongoing work and conclusions.

2. Riacho Fundo: transition from a natural to an urban environment

The Riacho Fundo is a small basin (225,48 km^2) in Brasília, central Brazil. Since the new capital, Brasília, was built in the late 1950's, it has been the most impacted area of the Paranoa Lake water basin. Most of the impacts are related to changes in land use, that transformed natural areas into rural and urban areas, currently with ca. 200.000 inhabitants. Due to the urbanization process, springs, streams and natural vegetation are disappearing, and biodiversity is being reduced. Changes in habitat put high pressure on many species, including the Riacho Fundo's largest mammal, the capybara (*Hydrochoerus hycrochaeris*).

Most of the economic activities in the area are related to services, including business offices, commerce and automotive service garages. Garages are often responsible for soil and water contamination with petroleum-based products. Despite their small scale in the Riacho Fundo, industrial activities and agriculture have significant impacts. Most of industries is related to food and clothes production and contributes effluents rich in organic matter and chemical pollutants into rivers and streams. Agriculture is based on corn and vegetables production, resulting in soil and water contamination with pesticides. Cattle, pork, and chicken are the most important livestock in the basin. Runoff of animal waste may cause eutrophication of water bodies. Details about the the Riacho Fundo basin can be found in Salles and Caldas (2006).

According to the stakeholders the most relevant problems in the basin are: (1) uncontrolled land occupation; (2) deforestation and destruction of natural habitats; (3) problems with basic sanitation (including garbage and sewage deposition in open land and water bodies) and lack of adequate rain-water drainage system; (4) unsustainable practices by farmers and by the industrial sector; and (5) deficit in community participation, in part due to lack of knowledge about local degradation processes and environmental concern (Salles, 2001).

3. Assumptions and perspectives in qualititative models

Given the large amount of knowledge involved in the discussion about sustainability it is necessary to organize such knowledge in order to create meaningful sets of simulation models to support stakeholders. The solution proposed here is to build up *perspectives* using modelling assumptions.

3.1 Perspectives

Given a large qualitative model about sustainability, a perspective defines a subset of simulation models that can be created to achieve a particular goal, that is, to answer questions of a particular type. Creating a perspective requires the selection of a sub-system within the larger system of interest, which includes a sub-set of entities and potentially a sub-set of the entities' features (quantities).

Perspectives serve an organizational function that, once the properties of a perspective are defined, guides the modeller in selecting appropriate assumptions, structural relations and scenarios. Perspectives are thus useful not only in defining and constraining a simulation, but also to automate the search of model fragments in a library, taking into consideration certain aspects of the encoded knowledge while ignoring the rest. Depending on which perspective is adopted, different entities, quantities, values, and causal relationships are included in the simulation. For the Riacho Fundo model, three perspectives were defined – *Rural*, *Semi-urban*, and *Urban* – each focusing on particular combinations of environmental, economic and social phenomena.

Perspectives can be implemented using explicitly represented assumptions and other modeling primitives, including hierarchies of entities and model fragments, attributes, alternative quantity spaces for key quantities and alternative representations of key concepts. The consequences of adopting a given perspective in a simulation are determined automatically by the reasoning engine based on the encapsulated knowledge relevant to the perspective (Bredeweg *et al*. 2006).

3.2 Assumptions

Conceptually, modelling assumptions fall into two categories: simplifying and operating assumptions (Falkenhainer and Forbus, 1991). *Simplifying assumptions* are used to make explicit how knowledge details such as the underlying perspective, approximations, and level of granularity are represented in the model fragments. Simplifying assumptions are classified as (a) *ontological* assumptions, to provide the vocabulary used in the model, explicating what kinds of things exist and what sort of relationships between them can be held; (b) *grain* assumptions, to define the level of details represented in the model, perhaps aggregating some features and ignoring others; (c) *approximation* assumptions, to make models that are easy to use, sometimes at the cost of accuracy; and, often intertwined with approximation assumptions, (d) *abstraction* assumptions, used to reduce the complexity of the modelling language, usually reducing information available and increasing ambiguity.

Operating assumptions are used to manage complexity. In a way, they give focus to the simulation, by implementing constraints so that the model describes the behaviour relevant for answering specific questions. Three types of operating assumptions are considered here: (a) *local restrictions*: restrictions on quantity values implemented by means of inequalities between quantities and constants (e.g. *number_of* >0); (b) *operation mode*: a 'general assumption' that controls a collection of local restrictions; and (c) *steady-state* assumptions: determine that all derivatives for some class of parameters have value zero. Ultimately, operating assumptions increase the efficiency of the simulation by ruling out entire classes of behaviour (e.g. immigration and emigration in closed population dynamics), and by indicating the range of parameter values for which certain approximations are valid (e.g. birth rate can only exist when *number_of* >0).

3.3 Garp3

The model was implemented in Garp3 (www.garp3.org), a qualitative reasoning workbench that provides a graphical interface for building models and inspecting simulations (Bredeweg *et al*., 2006). Garp3 models are created around entities, modelling primitives used to represent relevant objects of interest. Their continuous properties are represented as quantities. Possible qualitative values are represented in quantity spaces (QS), typically an ordered set of points and intervals. It may happen that specific values of two quantities always co-occur, as for example, the number of individuals and the biomass of the population. This notion is captured by means of correspondences, that can involve specific values or the whole quantity space, and can be either direct (e.g. *large* corresponds to *large*) or inverse (e.g. *large* corresponds to *small*).

Following Forbus (1984), it is assumed that changes in the system are initiated by processes, which are modelled as direct influences (*I*±). Qualitative proportionalities propagate the effects of processes to other quantities (*P*±). Knowledge is represented in model fragments automatically selected by Garp3 to create representations of qualitative states of the system during a simulation. A particular type of model fragment, Agent, is used to model external factors that cause changes in the system. Both entities and model fragments are organized in a hierarchical way, so that features described at higher levels are inherited by the lower levels. A scenario describes the system structure and initial values of some quantities to be considered in the simulation. Garp3 allows for representations of exogenous variables in the scenario, assigning them complex behaviour (e.g. random or sinusoidal) that is not motivated within the system being modelled (Bredeweg *et al*., 2007).

Garp3 provides two useful modelling primitives to enforce the selection of certain model fragments: assumptions and attributes. An assumption identifies specific model fragments that implement particular features or conditions for causal relations (influences and proportionalities) to become active. Attributes are special labels that can be attached to a particular entity for defining features that can take fixed values, so that different instances of the same entity can be created. Both assumptions and attributtes should be included in the scenario in order to activate model fragments with the same assumptions and attributes during the simulation.

4. Describing the Riacho Fundo model

Four perspectives are defined to organize the library of model fragments about sustainable development in Naturnet-Redime case studies: *Natural*, *Rural*, *Urban* and *Social*. The *Natural* perspective relates to natural phenomena, including ecosystem services (Daily *et al*., 1997; Alcamo *et al*., 2005). The *Rural* perspective focus on human activities aiming at exploring natural resources for economic purposes (Castells, 1996; Garrity, 2004). The *Urban* perspective addresses the city and its physical and communications infrastructure, its dependence on resources coming from outside and its own metabolism, as discussed by Egger (2006). Finally, the *Social* perspective is related to economy, governance, culture and human well being (Colby, 1991; Castells, 1996; Dodds, 1997; Egger, 2006). It is possible to have elements from all of the four perspectives combined in a single simulation model. Note that the Riacho Fundo model includes two of these four perspectives (*Rural* and *Urban*) and the *Semi-urban* perspective. Elements of *Social* and *Natural* are combined to the other perspectives.

Table 1 summarizes the main concepts addressed in each perspective of the Riacho Fundo model, selected in accordance to expert and stakeholders' opinions as discussed in section 2.

	Perspectives		
Land use	*Urban*	*Semi-urban*	*Rural*
Main problems	Drainage system; flooded areas; transported garbage and damage caused by floods	Urbanization; water infiltration; and soil erosion	Erosion; loss of water resources and biodiversity
Economic features	Services: garages	Industry: textile and food industries	Agriculture: cattle; crops
Soil	Impermeable soil	Soil particle aggregation	Soil fertility
Water resources	Effects of uncontrolled flow of water run off and of the drainage system	Effects of erosion and underground water on springs and rivers	Effects of erosion and underground water on springs and streams
Biological entities	Mosquitos, Pathogens	Vegetation	Vegetation; Vertebrates; Capybara
Human	Economic activities; Human well-being: garbage and water related diseases	Economic activities	Economic activities
Agents	Rainfall	Urbanization	--
Sustainability	Control of diseases; Control of residues	Water quality; Control of residues	Soil fertilization; Reuse of residues

Table 1. Overview of the main concepts addressed by the Riacho Fundo model.

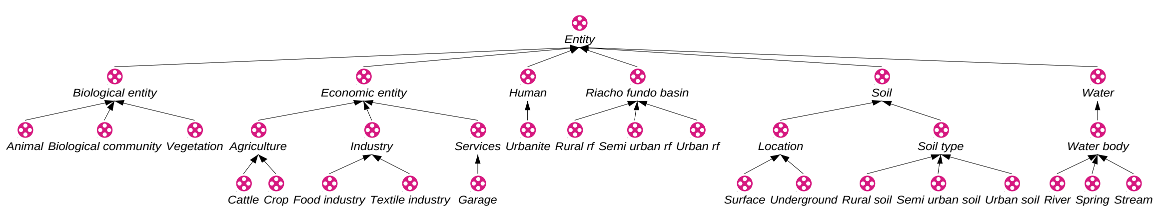

Figure 1. Entities used in the Riacho Fundo model.

4.1 Entities

The system structure is representated with entities and configurations in Garp3 models. Figure 1 shows the entity hierarchy used in the Riacho Fundo model.

Three entities define the implementation of perspectives as discussed in section 3: 'Rural rf', 'Semi-urban rf' and 'Urban rf'. These entities represent types of land use, and are associated to three types of soil: 'Rural soil', 'Semi-urban soil' and 'Urban soil'. Economic activities are represented by the entities 'Agriculture', 'Industry' and 'Services', respectively associated to each type of land use. Other entities represent relevant types of biological resources and water bodies, and a particular type of human being, the urbanites. Figure 2, a screenshot of a simulation in Garp3, shows the complete Riacho Fundo system structure. Simulation models created in the three perspectives explore part of this system structure, as discussed in the following sections.

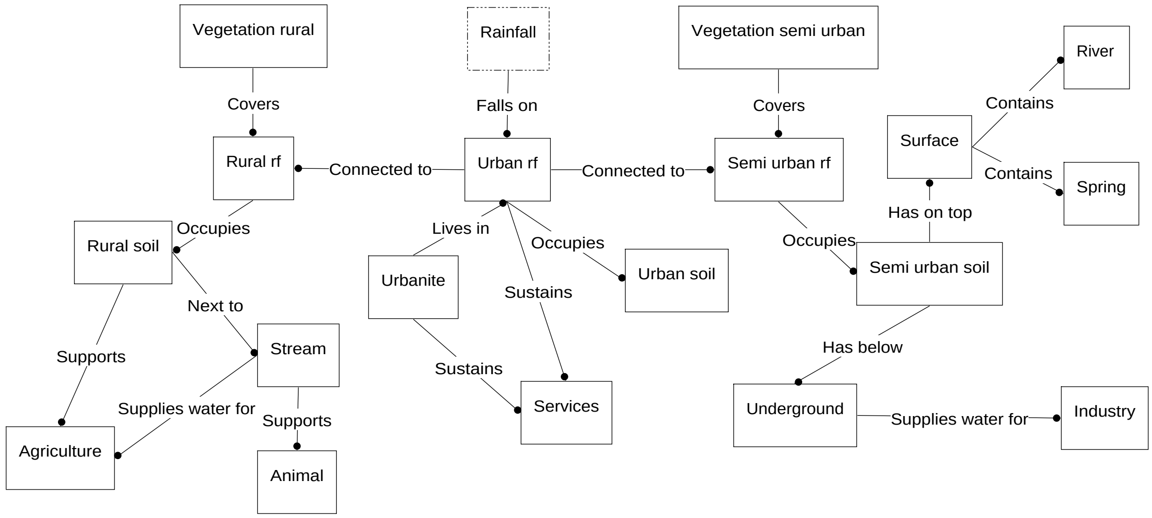

Figure 2. System structure showing all the entities and configurations included in the Riacho Fundo model.

4.2 The *Rural* perspective

Changes in vegetation cover drive the dynamics of soil fertility, water, biodiversity and the agricultural production in the *Rural* perspective. Initially, the balance between regeneration and degradation of the vegetation determines the vegetation growth process and set the value of *Growth rate*, a direct influence on *Vegetation cover*. This quantity has a negative effect on the area degraded by erosion by means of influencing soil particles aggregation, modelled with two proportionalities: P+(*Level of aggregation*, *Vegetation cover*) and P–(*Eroded land*, *Level of aggregation*). When *Eroded land* increases, it causes the amount of nutrients in the soil to decrease, which in turn causes the quantity *Fertility* to decrease.

Agriculture is represented in the model as cattle and crop production. Resource inflow for cattle production comes from soil fertility; residues produced by cattle can either become organic pollution in water bodies or be used as manure to add nutrients to soil fertility and as such become part of the resource inflow for agriculture. Crop production depends on irrigation, being the water abstracted from a water body; residues are associated to pesticides and may also pollute water bodies.

Erosion triggers another causal chain, leading to sediment deposition in water bodies. A simplified version of erosion associates soil aggregation to the quantity *Removed soil* via a positive proportionality: P+(*Removed soil*, *Level of aggregation*). Next, *Removed soil* is connected to the quantity *Sediment* of the entities ‘Spring’ and ‘Stream’ in separate model fragments, allowing for simulations that explore the consequences of erosion for both types of water bodies, either together or separate.

Depth and amount of water in streams in the Riacho Fundo basin have been associated to the survival of animals, in particular of capybaras. Such relation is captured in two ways. A simplified version is implemented by means of proportionalities in the causal chain *Amount of water* → *Vertebrate survival* → *Animal biodiversity*. A detailed version describes the animal population growth process (reusing a generic model fragment that applies to all biological entities, e.g. vegetation).

4.3 The *Semi-urban* perspective

Large areas of the Riacho Fundo basin are changing due to urbanization. Models in the *Semi-urban* perspective capture this pressure to provide a different view on features already addressed by the *Rural* perspective, such as soil aggregation and erosion and their consequences to water bodies and to economic activities in the basin.

Soil aggregation is represented as a process, in which the rate is influenced by an agent (Urbanization), and a negative feedback is used to assure that the process stops when the level of aggregation reaches its maximum value. This detailed description is important to set the effects of urbanization on two other processes: water infiltration and erosion. The quantity *Level of aggregation* influences the infiltration and erosion processes via their rates: when aggregation increases, both infiltration rate and erosion rate decrease. The basic mechanism of water infiltration in the soil is represented in Figure 3.

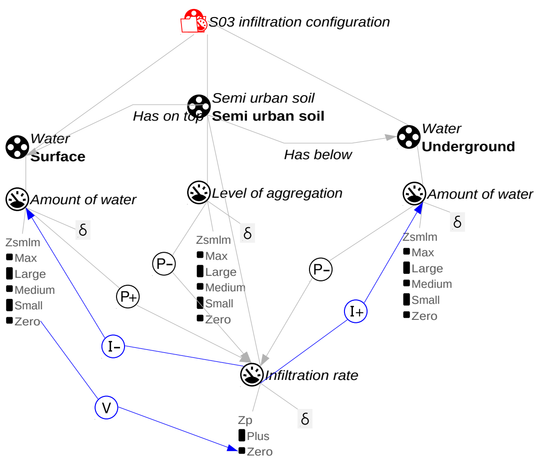

Figure 3. Model fragment representing the Infiltration process.

Two other model fragments are used to make explicit the conditions for this process to become active: in 'Infiltration active', if the inequalities *Amount of water > zero* (at the surface) and *Level of aggregation < maximum* hold, the rate gets the value *plus*; in 'Infiltration inactive', if *Amount of water = maximum* (at the underground), then *Infiltration rate = zero*. This mechanism implements the notion of saturation, useful function for modelling biological systems (Haefner, 2005).

Water supply for industrial activities comes from different sources: springs, river and underground water. Two types of industries are included in the Riacho Fundo *Semi-urban* perspective: textile and food processing. Pollutants produced by these industries include chemical and organic substances.

4.4 The *Urban* perspective

The main aspect explored by the *Urban* perspective are the effects of an engineered drainage system. Pairs of scenarios show the outcomes of a particular situation in which the uncontrolled flow of rain water affects different aspects of urban areas, both with and without the drainage system.

Two direct consequences of uncontrolled water are represented in the model: garbage transportation and floods. Garbage is seem as residues from economic activities. Economic damages caused by floods include the destruction of public and private assets. Quantity *Flooded areas* stimulates the increase of mosquito populations, and some of them can be associated to diseases such as dengue fever, a real problem in the Riacho Fundo basin. However, the current version of the model represents only the increase of generic pathogens, that may cause a number of water related diseases.

Finally, the quality of life of the urbanites is represented as a balance between generic positive and negative factors, used to calculate the rate of the improvement of life quality process, and this quantity is a positive direct influence on *Well-being*. In the current implementation of the model, garbage and pathogens are associated to the negative factors, and specific assumptions are used to control the interaction between these quantities.

4.5 Economic activities

Economic activities are modelled in generic terms so that a unique set of model fragments can be reused to represent different activities. Input of resources is represented by the quantity *Resource inflow*, and the use of resources, by *Resource consumption*. A qualitative subtraction combines these two quantities to calculate the value of *Production rate*. This rate may cause the quantities *Product* and *Residue* to increase, decrease or remain stable. This model fragment is shown in Figure 4:

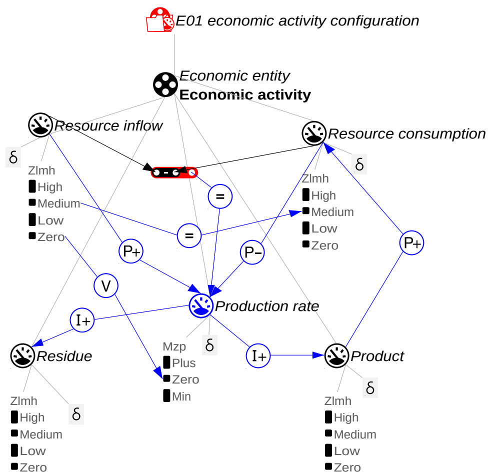

Figure 4. Model fragment representing a generic economic production process.

Additional model fragments define specific types of products and residues related to economic activities. For example, residue produced by the cattle is organic matter that can be used as fertilizer. Accordingly, a model fragment represents *Manure* as corresponding to *Residue*. Similar model fragments implement correspondences to *Pesticides*, *Chemical pollution*, *Organic pollution* and other quantities according to the type of economic activity.

5. Simulating sustainability in Riacho Fundo

The current implementation of the model supports 48 simulations, exploring the three perspectives. Within each perspective, simulations exhibit increasing levels of complexity. Initially only basic processes and mechanisms are simulated. Next, different basic processes are combined with other elements in order to compose more complex simulation models, building up the knowledge available in the library until an overview of the perspective is achieved. Due to space restrictions only one simulation is described in detail here. More details are available at www.naturnet.org.

5.1 *Rural* perspective

Simple simulations explore, for example, only vegetation dynamics (four quantities); vegetation, eroded land and fertility (eight quantities); erosion, stream and biodiversity (10 quantities); vegetation, erosion, and fertility determined by soil nutrients and manure (14 quantities). The more complex simulation in the current implementation of the model involves 20 quantities related to vegetation, erosion, biodiversity and fertility.

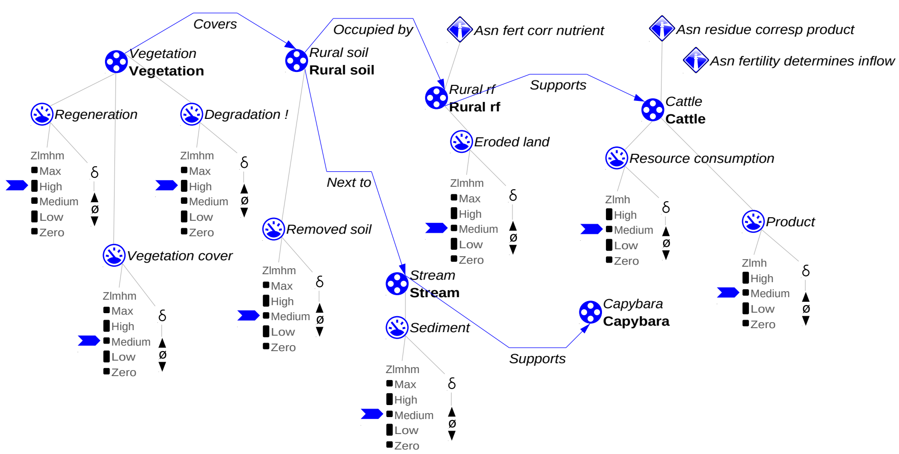

Figure 5. Initial scenario ‘Vegetation, erosion, biodiversity and resource inflow determined by fertility’, from the *Rural* perspective on sustainability in Riacho Fundo.

Figure 5 shows this intial scenario. The following assumptions hold in this scenario: ‘Fertility corresponds to nutrient’, ‘Fertility determines (resource) inflow’ and ‘Residues correspond to product’. The exclamation mark that follows the quantity *Degradation* indicates its behaviour is assumed to be exogenously driven (Bredeweg *et al.*, 2007), in this case, constant. The simulation involves 20 quantities and produces three initial states; the full simulation, 85 states.

As in the scenario the initial values of *Regeneration* and *Degradation* are in the interval *high*, the situation is ambiguous and the value of *Vegetation cover* is undefined. Accordingly, in the initial states, the system may be in equilibrium, with *Vegetation cover* and all the quantities constant and steady (state 1), or *Vegetation cover* can be either increasing (state 2) or decreasing (state 3). The causal model, as it appears in state 3, is shown in Figure 6. The causal model shows that *Growth rate* is negative and *Vegetation cover* has value <*medium,–* >.

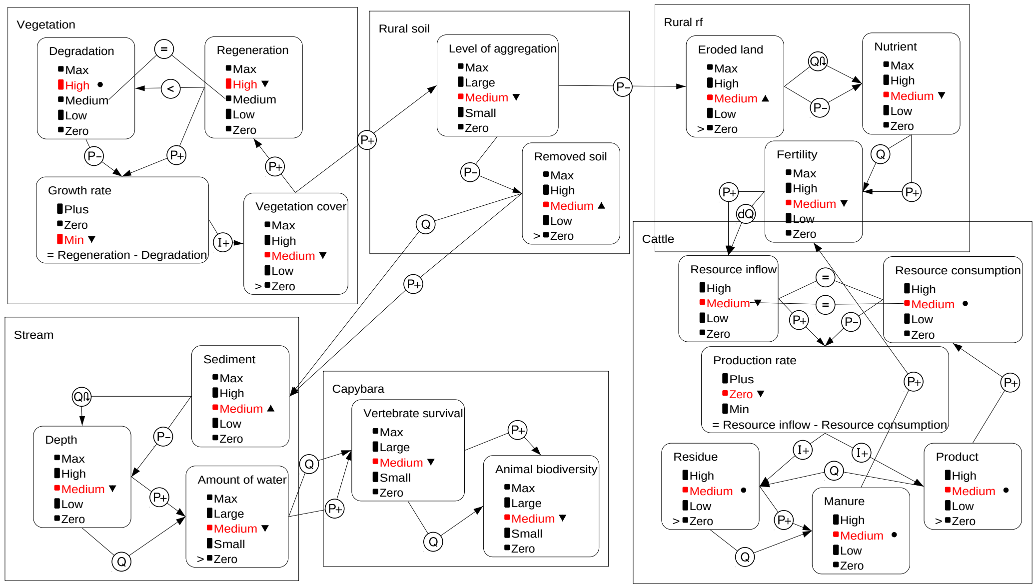

Figure 6. Causal model as it appears in state 3 of the simulation 'Vegetation, erosion, biodiversity and resource inflow determined by fertility', *Rural* perspective.

As a consequence, *Level of aggregation* also decreases, and this tendency propagates in two causal chains. On the one side, *Removed soil* and the amount of *Sediment* in the stream increase, and *Depth* decreases. *Amount of water* also decreases, a tendency that propagates to both *Vertebrate survival* and *Animal biodiversity*. On the other side of the causal chain, soil aggregation causes *Eroded land* to increase, leading *Nutrient* and *Fertility* to decrease. Note that *Fertility* could also be influenced by *Manure*, but is this particular state the latter quantity is steady, so the proportionality is inactive. Following the assumption 'Fertility determines (resource) inflow', *Resource inflow* is decreasing and, as a consequence, the equilibrium between this quantity and *Resource consumption* is broken. *Production rate*, which has the value zero, will decrease in the following state (in this state it has a negative derivative). *Production rate = zero* means that both *Product* and *Residue* are steady, and the proportionalities put by these quantities on *Resource consumption* and *Manure*, respectively, are inactive.

One of the possible outcomes of this simulation is the behaviour path [3 → 4 → 11 → 22 → 81 → 82]. In this case, *Vegetation cover* goes to *zero* and *Removed* soil goes to *maximum*, eventually causing the disappearance of the stream and of capybaras, representing biodiversity loss. Similarly, *Eroded land* also goes to *maximum*, *Fertility* goes to *zero* and the whole productive system collapses. The values of relevant quantities in this path are shown in Figure 7. A behaviour path starting in state 2 produces basically opposite results: *Vegetation cover* increases, and reduces the erosion process. As a consequence, either the amount of water in the stream may go to *maximum*, leading biodiversity to higher values as well, or soil fertility also goes to *maximum*, leading the cattle production to higher levels. (Figure 8).

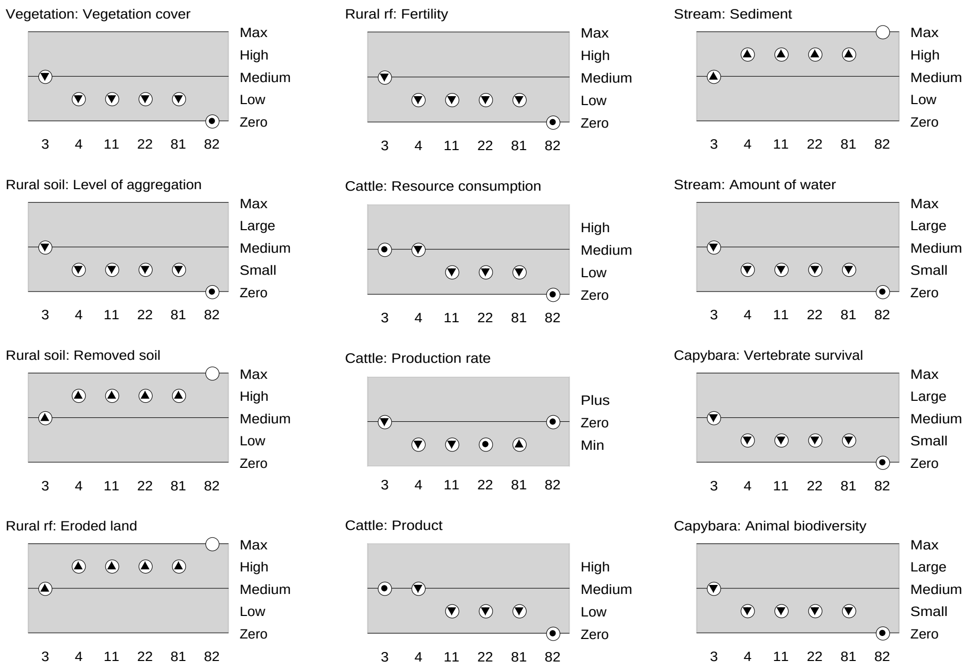

Figure 7. Value history of selected quantities in a simulation ‘Vegetation, erosion, biodiversity and resource inflow determined by fertility’, *Rural* perspective.

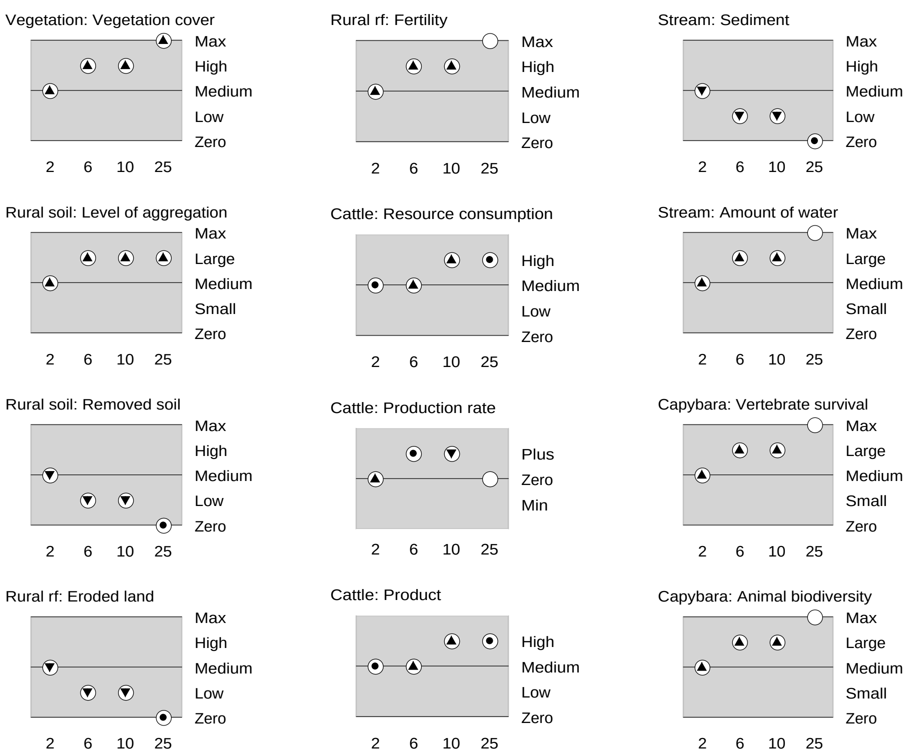

Figure 8. Value history of selected quantities in a simulation ‘Vegetation, erosion, biodiversity and resource inflow determined by fertility’, *Rural* perspective.

5.2 *Semi-urban* perspective

Simulations exploring only one process or basic components in the *Semi-urban* perspective show the aggregation process (two quantities), infiltration (five quantities) and erosion (five quantities). Complexity increases when erosion and the conditions of springs (eight quantities), or infiltration and springs (11 quantities) are combined, and when economic activities are included.

Figure 9 shows the causal model for a simulation that includes the effects of erosion on springs and on the water is being supplied to the food industry (14 quantities). In this simulation, for example, one of the behaviour paths show that, although the level of aggregation increases and erosion rate decreases, the amount of removed soil goes up to *maximum* and eventually causes the amount of water in the spring to become *zero*. As this is the main resource for the industry, production also goes to *zero* and the whole productive system collapses.

5.3 *Urban* perspective

Simulations in this perspective allow comparison of situations in which there is no drainage system, to those in which the flow of controlled water is increasing. The simplest simulations demonstrate the mechanism of drainage (involving seven quantities), production of garbage (seven quantities), growth of mosquito populations (two quantities or four quantities, if the details of the process are included), and the mechanism of well-being improvement (four quantities). Simulations with intermediate level of complexity explore, for instance, the importance of the drainage system for: controlling flooded areas and water related diseases (eight quantities); mosquito populations (nine quantities); eliminating garbage transportation (15 quantities) and, in doing that, to reduce negative factors on well-being (19 quantities). The most complex simulations in the current implementation (Figure 10) involve 22 quantities and include all the elements mentioned in section 4.4.

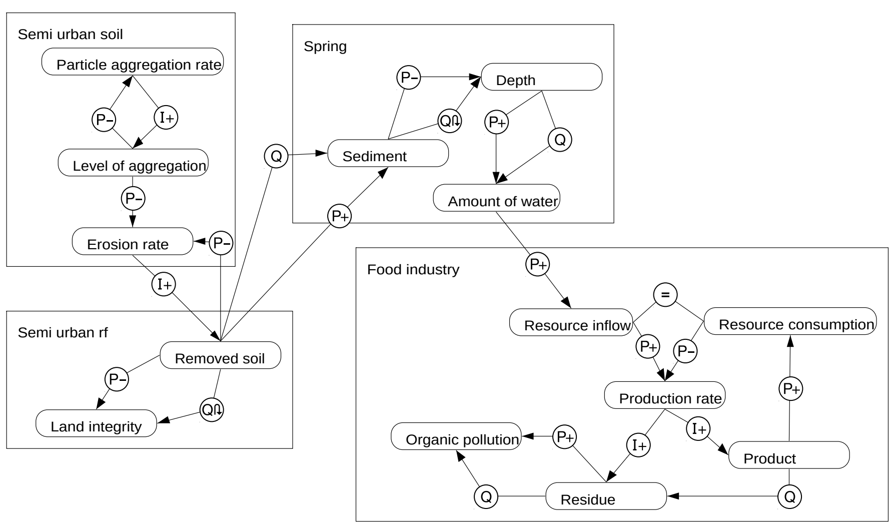

Figure 9. Causal model obtained in state 5 of the simulation ‘Erosion, springs and water supply to food industry”, *Semi-urban* perspective.

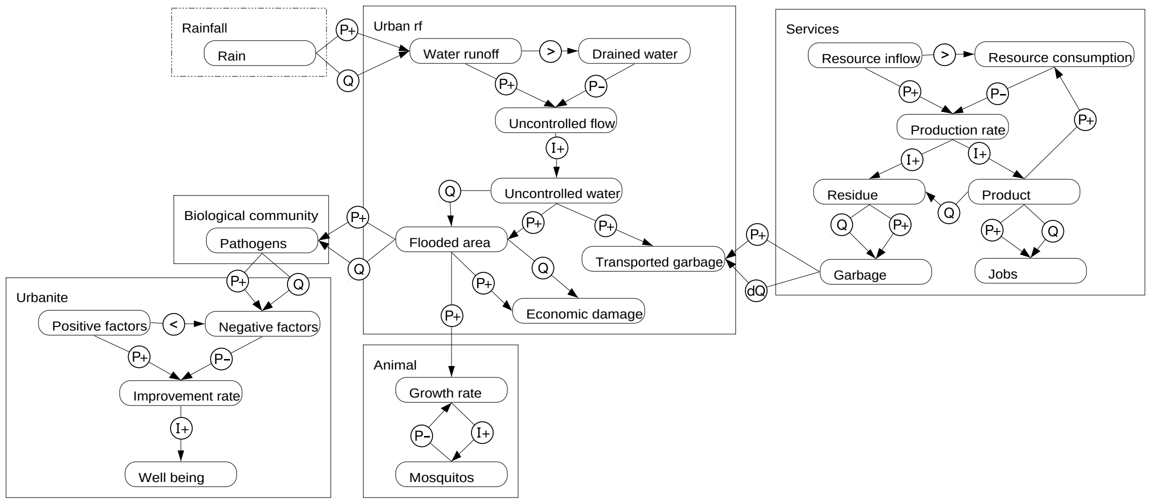

Figure 10. Causal model obtained in state 1 of the simulation 'Drainage increasing, transported garbage and well-being', *Urban* perspective.

In this simulation, it is assumed that *Rain* and *Water runoff* are constant and steady (<*medium,0*>) and *Drained water* starts in zero, but increasing. Until this quantity reaches the value *medium*, the overall situation worsens, with increasing values of quantities such as *Flooded area*, *Economic damage* and *Negative factors* on well-being. However, as soon as *Drained water* > *Water runoff*, the situation improves and, at the end of the simulation, *Well-being* has value *high*.

6. Discussion

This paper describes the use of perspectives to organize a large library of model fragments in order to create sets of simulation models each addressing a class of sustainability issues in the Riacho Fundo basin. Three perspectives (*Rural*, *Semi-urban* and *Urban*) are taken to represent different types of land use, and a wide range of assumptions were defined to implement these perspectives.

The use of assumptions for reasoning with multiple models has a long tradition in Qualitative Reasoning (Bobrow, 1984). de Kleer and Brown (1984) point out the importance of making modelling assumptions explicit and of changing them during problem solving. A number of authors have been working on developing algorithms for automatically selecting or changing models according to certain assumptions. For example, Addanki *et al*. (1991) represent domain knowledge as graph of models and change assumptions to move from one model to the other; and Liu and Farley (1991) took a different approach to automate task-driven reasoning about physical systems using multiple perspectives. Falkenhainer and Forbus (1991) developed compositional modelling, a technique to decompose domain knowledge into model fragments, and implemented an algorithm for model composition given a domain theory, a structural description of the system and a query to be answered. Rickel and Porter (1997), using the compositional modelling approach, developed an algorithm to build the simplest adequate model from building blocks (single variables and influences) for answering prediction questions within a certain time scale, and tested it in the domain of botany and plant physiology.

Differently from these previous approaches, the work described here addresses sustainability using no numerical information or mathematical functions to define perspectives or to implement assumptions, only qualitative representations of concepts. Garp3's representational *apparatus* and algorithm are explored to capture ecological knowledge and to create alternative models according to the perspective taken. The first element used to create a simulation model taking a certain perspective are the entities 'Rural rf', 'Semi-urban rf' and'Urban rf'. Increasing levels of complexity can be further obtained by means of the inclusion of new entities in the system structure.

In fact, control over entities and quantities introduced in the model is an important and quite effective use of simplifying assumptions to implement perpectives. Considering that: each entity can be associated to a number of quantities; each quantity can be modelled using different quantity spaces; and each qualitative value represents a qualitative state of the entity, the choice of entities, quantities and quantity space defines specific vocabulary for a certain perspective. For example, different types of economic activities can be associated to any perspective taken in the Riacho Fundo model (section 4.1). Besides that, the set of model fragments created to identify residues produced by different types of economic activities (section 4.5) provides adequate vocabulary for each perpective. This way, entities 'Urban rf' and 'Garage' used in *Urban* perspective introduce vocabulary to describe how garbage produced can be transported by uncontrolled rain water runoff and affect human well being.

Grain assumptions provide different levels of details to some relevant phenomena that reappear in different contexts. Erosion is a well developed example in the Riacho Fundo model. When the *Semi-urban* perspective is taken (section 5.2), the soil aggregation process defines the value of *Level of Aggregation*, which in turn influences *Erosion rate*, and this process defines the value of *Removed soil*. A less detailed representation is adopted in *Rural* perspective models (section 5.1): *Vegetation cover* indirectly influences *Level of Aggregation* and this quantity also indirectly influences *Removed soil*. Similar options are available to represent population growth of capybara (section 5.1) and mosquitos (section 5.3).

Closely related to these assumptions, approximations can produce simpler accounts for the same phenomenum that are easier to use at the cost of accuracy. For example, disappearance of springs can be addressed in simulation models when both *Rural* and *Semi-urban* perspectives are taken (sections 4.2 and 4.3). As processes soil aggregation and erosion are not explicitly described in the *Rural* perspective, a model on this topic is easier to use than a similar model in the *Semi-urban* perspective.

Operating assumptions can be used both to give focus and to reduce the complexity of the simulations. For example, in the *Semi-urban* perspective models disappearance of functional springs can be caused by erosion and/or lack of undergroung water (Figure 3). Garp3 model ingredient Attributes was used to capture these possibilities: entity 'Spring' has an attribute 'Focus', with two possible values: 'Effects of erosion' and 'Effects of infiltration'. Depending on the attribute value introduced in the scenario, two independent causal chains may become active: (a) 'Focus: Effect of erosion': *Level of aggregation* → *Removed soil* → *Sediment* → *Depth* → *Amount of water*; (b) 'Focus: Effect of infiltration': *Level of aggregation* → *Underground water* → *Amount of water*. An additional model fragment, in which 'Springs' has no attributes, allows for expressing simultaneous effects of erosion and infiltration on the springs.

Similarly, different causal chains can be constructed within the *Rural* perspective, depending on the use of focus operating assumptions. Soil fertility can be determined in three ways: (a) by assuming that *Fertility* values correspond to *Nutrient* values; (b) by considering that vegetation cover determines the amount of organic matter, and calculating *Fertility* = *Organic matter* + *Nutrient*; and (c) by considering the combination of nutrients and manure, a by-product of cattle livestock (see Figures 6-8). Two assumptions take care of options (a) and (b). If no assumption is introduced in the scenario, option (c) is selected.

Operating assumptions are used to reduce complexity in simulations either by reducing ambiguity or preventing some behaviours to happen. Local restrictions, implemented as correspondences, were widely used in the Riacho Fundo model to reduce ambiguity and, as such, to reduce the number of states in the simulation. For example, directed correspondences between quantity values express co-occurences of values *zero* (e.g. Figures 3 and 4); correspondences between quantity spaces, co-occurrence of all possible values of two quantities (see 'Q' relations in Figures 6, 9 and 10). Inverse correspondences represent co-occurrence of opposite values of two quantities (see, for example, the Q↓ relation between *Sediment* and *Depth* in Figures 6 and 9). Finally, correspondences between derivatives significantly reduce ambiguity in the simulation, as they determine the strongest influence when two or more proportionalities apply to the same quantity. For example, it was used to enforce *Transported garbage* to take the value of the derivative of *Garbage*, and not of *Uncontrolled water* in *Urban* perspective (see the dQ relation in Figure 10).

Local restrictions may also be implemented by means of inequalities. Examples include definitions of the level of pollution produced by economic activities: a fair level is set by assuming *Residue* < *medium*, no matter the amount of products; less sustainable options are *Product* ≤ *Residue* and *Residue* corresponds to *Product* (correspondence between the quantity spaces of the two quantities). As these assumptions are implemented at the level of 'Economic entity', they are applicable to the three perspectives.

Steady state assumptions reduce complexity by giving a unique behaviour to a quantity (decreasing, steady, increasing), and can be implemented both as exogenous quantities and in model fragments. An example of the former is presented in Figure 5, a scenario in which the quantity *Degradation* which is assumed to have value *high* constant. Note that exogenous quantities may express more complex behaviours (Bredeweg *et al*., 2007) Steady state assumptions may also involve quantity magnitudes or derivatives when implemented in model fragments. In the Riacho Fundo model examples may be found in the three perspectives (e.g. *Drained water* = <*zero*, *zero*> and *Drained water* = <*?, +*> in *Urban* perspective).

The contents of the Riacho Fundo model is in accordance to stakeholders demands (section 2). From the technical point of view, perspective-taken simulation models correctly provide views to sustainability in the basin. Assumptions are conceptually clear and pedagogical. However, some problems remain. Models implementing *Natural* and *Social perspectives* are still lacking. The use of hierarchies of model fragments and entities and of other modelling primitives should be optimized. Integration of perspectives is an issue, as ambiguity surfaces when unrelated quantities are included in the same simulation model. New modelling assumtions will become necessary to take care of integrated simulations. A point that was not addressed here was the issue of shifting from one perspective to another. Identifying the requirements for such transitions will lead to better understand the nature of perspective-taking in qualitative reasoning (Liu and Farley, 1991).

7. Conclusions

The Riacho Fundo model comprises, in its current implementation, 33 entities, 9 processes and 48 quantities, organized in 112 model fragments. It has 48 scenarios that simulate different subsets of the whole system structure. The three perspectives – *Urban*, *Semi-urban* and *Rural* – proved to be efficient in creating simulations about relevant aspects of sustainability in the Riacho Fundo basin.

Simplifying assumptions facilitate vocabulary creation for each perspective, as they are used to control how entities, quantities and quantity values are introduced in the simulations. Assumptions are also effective to implement alternative views on similar phenomena, shifting from coarse to fine grained representations, according to the perspective taken. Operating assumptions provide focus and reduce complexity of simulations within each perspective.

Garp3 is an interesting tool for implementing compositional models, as it provides a rich modelling language for expressing both model components and assumptions constraining their use. Some of Garp3 modelling primitives, such as entities and configurations, attributes and agents are particularly useful for implementing perspectives. Model fragments, inequality relations, correspondences and exogenous quantities are particularly suited for implementing both simplifying and operating assumptions. This way, besides being functionally important, assumptions were also conceptually aligned to the rest of the domain knowledge represented in the library.

Lessons learned during the modelling effort described here will be useful for improving stakeholders' understanding about the problems they face. Sustainability is a complex issue, and learning about its multitudinous aspects is an intergenerational commitment for the current generation, that should properly take care of river basins still rich in natural resources and rehabilitate the damaged ones, while promoting human development for those who live in these areas.

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