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[1] AUTHORS: Paulo Salles and Ana Luiza Rios Caldas

Abstract

This document presents the structural model for the Riacho Fundo basin case study. A contextualized introductory overview is presented, including a number of relevant problems related to the sustainability in the Riacho Fundo basin. Based on the problems identified, a generic structural model with entities and relations is detailed. Three examples of causal models are described, including processes, quantities, agents and scenarios that can be used to represent specific situations found in the Riacho Fundo basin: drying up the springs; consequences of torrents in urban areas, including contamination with pathogens, and erosion of deforested areas that causes stream sedimentation and loss of land fertility.

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Content

1 INTRODUCTION

The Riacho Fundo basin is located in Brasilia, the Brazilian capital, in the middle of the Cerrado, the second largest Brazilian biome. There are two well distinct seasons in the region, a dry and colder season from May to September, and a rainy and warmer season, from October to April. According to Köppen classification, climate is wet tropical savanna (Aw) and wet temperate with dry winter (Cwhl).

With approximately 15 km of extension, this small river is influenced by more than ten urban areas: Guará, Park Way Mansion Sector, Núcleo Bandeirante, Vila Metropolitana, Candangolândia, Setor de Indústrias e Abastecimento, Taguatinga, Estrutural, Riacho Fundo I and Riacho Fundo II (Batista, 2004). The stream springs are surrounded by the last two cities. Lack of infrastructure in these cities leads to degradation of water resources, and the pollution brings several problems, including the contamination of crops produced in that area and sold to the population. Nearly all tributaries of Riacho Fundo present a high degree of eutrophyzation due to the discharge of sewage and garbage (Silva, 2000). Also, erosion is found all over the Riacho Fundo sub-basin. This way, Riacho Fundo stream is one of the most important agents of pollution and contamination of the Paranoá Lake. In this document, fundamental elements for the Riacho Fundo case study are presented, following the framework for conceptual qualitative reasoning description of case studies defined in Naturnet – Redime deliverable D.6.1 (Bredeweg *et al*., 2005).

Initially, in section 2, an overview of the Riacho Fundo basin is given. A summary of the most important problems of the basin, according to stakeholders that live in the area, is presented, and conceptual maps are used to organize ideas and to express our understanding of these problems. From them, relevant goals to be achieved with qualitative models are set. This material supports identification of relevant entities and relations between them that create the structure of the system to be modelled. A basic and general structure for the Riacho Fundo system, the definition of the system environment, relevant external influences and a set of assumptions are presented in section 3.

The global behaviour of the system is presented in section 4. Some processes associated to the main entities are defined and listed, relevant external agents are identified in order to design causal models about the most important issues in sustainable development in the Riacho Fundo case study. Causal models of three relevant problems are drawn to describe problems with the springs in the area, the urban drainage system and the erosion process. Based on these causal models, scenarios are defined and the predicted system behaviour is anticipated. Section 5 presents a detailed description of model elements: entities, quantities, quantity spaces, and fragments for each one of causal models proposed. The final part of the document presents our conclusions.

2 Initial specification of the Riacho Fundo basin case study

2.1 Documentation

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. It was progressively impacted by the transformation of rural into urban areas (Figure 1). These changes created a densely populated urban structure where few rural areas produce vegetables and protect springs and natural vegetation patches.

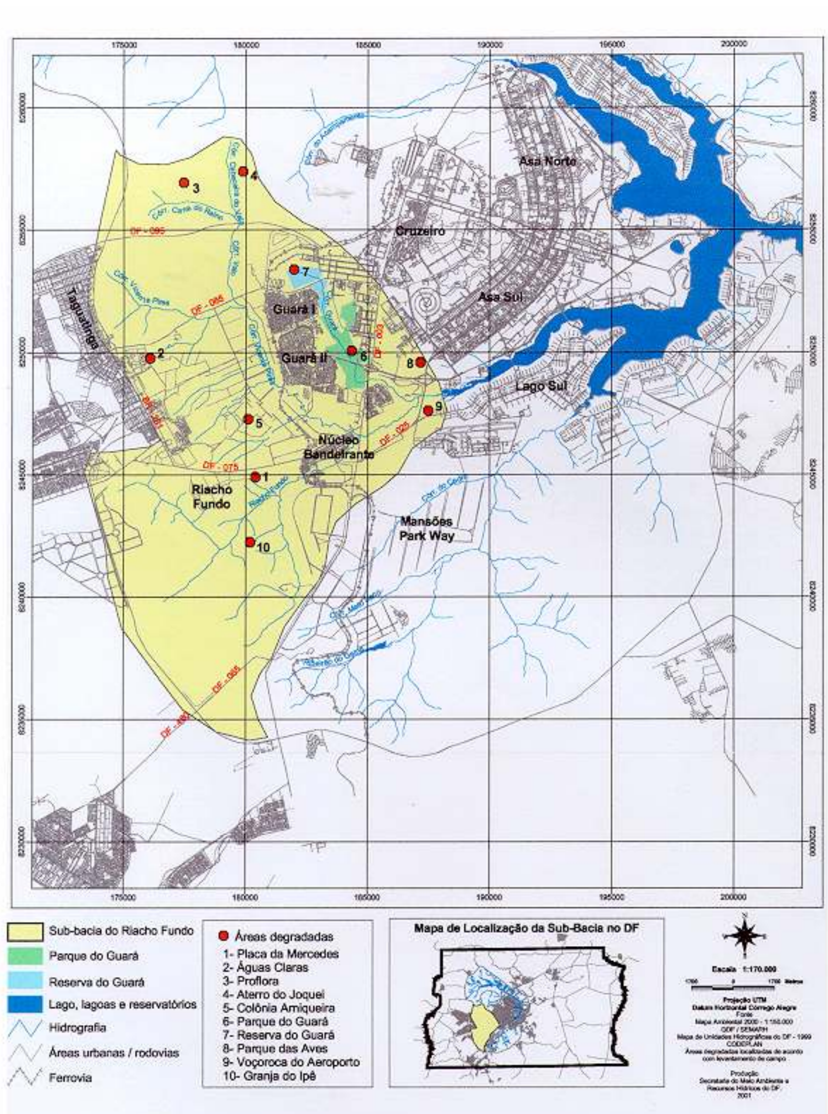

Figure 1. Location of degraded areas in the Riacho Fundo sub-basin, in the yellow map. External limits represent part of the Paranoá Lake water basin. (Fonseca, 2001. Available at <www.semarh.df.gov.br/ semarh/site/index.htm> Captured in 26/out/2005)

In the original plan for the Brasilia construction, a green belt with rural areas and patches of natural vegetation were planned in the north of Riacho Fundo basin. Together, these areas should form an ecological corridor, connecting the Brasilia

National Park (located at north of Brasilia) to the preserved areas in the southern part of the basin (Netto, 2001). However, recent studies show that irregular occupation of Riacho Fundo basin has promoted several impacts: riparian vegetation destruction, with loss of biodiversity; exploration of gravel pits and soil exposition leading to erosion; sediment deposits capable of modifying the river path; and garbage deposition in open areas (Netto, 2001).

2.1.1 Socioeconomic aspects of the Riacho Fundo basin

Most of the economic activities in the basin are related to the services sector, including commerce and public services. Agricultural activities are responsible for 1% of the average family income in the area, and industry for only 2,4%. In general, activities related to services have no great impact on the environment. However, in the Riacho Fundo basin there is a number of garages that are responsible for soil and water contamination with oil and petrol used by vehicles. Via the drainage network, these products affect small streams and the Riacho Fundo stream as well.

Between the cities Núcleo Bandeirante and Riacho Fundo, there are 237 public owned small farms, with 3,9 ha in average each. Some of these farms are being transformed into urban areas, but many still keep agricultural activities. Vegetable production is the main activity for most of these farmers. The consequences for the environment are soil and water contamination with bioicides and organic matter, and, sometimes, disequilibria in nutrient availability due to the use of fertilizers. Runoff of these materials may cause eutrophication in the water bodies of the basin.

Industrial activities are relatively small in the Riacho Fundo basin: there are some 280 companies related to industrial activities. However, they have significant impact on the environment. Most of these industries are related to food production, and their effluents are rich of organic matter. Other industries are related to fabric dye and clothes production. Some residues of this material are pollutant for the local environment.

2.1.2 Protected areas in the Riacho Fundo basin

The Riacho Fundo basin has been under heavy anthropogenic changes, but there are 14 legally protected areas, a decisive factor for conservation of remaining natural vegetation patches and for conservation of riparian forests alongside the river. These riparian forests play the role of corridors linking (protected) areas of natural vegetation within the basin and in other basins. Spatial continuity assures gene flow and biodiversity maintenance.

2.1.3 Abiotic environment in the Riacho Fundo basin

According to Fonseca (2001), the Riacho Fundo water basin covers an area of 225,48 km² in the cerrado biome. The main spring has coordinates 15° 52’ 59” S, 47° 57’ 19” W and the mouth is located at 15° 51’03” S, 48° 04’ 23” W coordinates (Medeiros, 1997). The average flow of water at the outlet is 4, 04 m³/sec. Precipitation is about 1.500 to 1.600 annual millimetres. Springs are located in an area favourable to underground water consumption, with an average outflow up to 12.000 litres per hour. The rest of the basin (including the river mouth) is less favorable, with an average outflow up to 4.500 liters per hour and a high incidence of dry (or almost dry) wells.

Cambissoils predominate in the highest part of the basin. This is an undeveloped soil, moderate declivity and 90-100 cm in depth, generally associated with the Campo limpo vegetation, a kind of open grassland. In the lower part of the basin, dark-red/yellow latossoils predominate. In this formation, soil is plain with light inclination. It is very thick, with moderate fertility, ancient evolution, and is associated with the forest-like physiognomies as Cerrado and Cerradão.

According to Philomeno (2003), dissolved oxygen is the main parameter for characterization of water pollution (by organic effluents) effects. The solubility of this gas in the water is determined by altitude and temperature. Values above the saturation point reflect algae photosynthetic activity, and values below the saturation point, the presence of organic matter being decomposed. The Riacho Fundo presented inadequate conditions for fish metabolism (low dissolved oxygen concentration) in the three depths (one, three and six meters) studied by Philomeno.

2.1.4 Biotic Community in the in the Riacho Fundo basin

The predominant plant physiognomies in the lower part of Riacho Fundo stream are riparian forest vegetations patches and wet fields, but portions of Campo limpo, Campo cerrado and Campo sujo can be also found with various degrees of perturbation (Silva, 2000). In degraded areas in the mouth of Riacho Fundo stream predominates the grass species *Brachiaria brizantha*, exotic for the Cerrado. The absence of bamboo is an indicator of the forest disturbance, since they do not tolerate direct solar light exposure (Silva, 2000).

With respect to the phytoplanctonic community, the permanent dominance of cyanobacteria – the 'blue' algae, observed for decades in the mouth of Riacho Fundo – is considered the last phase of eutrophization in a water body (Philomeno, 2003). Within the benthonic macroinvertebrate fauna of the Riacho Fundo stream molluscs are predominant. The invertebrate diversity (specially molluscs) found in the Riacho Fundo is typical of moderated polluted environments, in wet and dry periods (Medeiros, 1997).

The fish community is characterized by the presence of *Hasemania hanseni*, a little fish known as *piaba* (Ribeiro *et al.*, 2001). Despite the inadequate water condition for fish metabolism mentioned, other researchers showed the existence of larger fish communities in Riacho Fundo stream mouth, near the southern Sewage Treatment Plant (CAESB).

With respect to the mammal community, in the "Wild Life Sanctuary of Riacho Fundo" protected area a population boom of capybara (*Hydrochaeris hycrocaeris)* is expected by Reis and Juarez (2001), with 150 individuals, due to the absence of natural predators. This large number can contribute to trampling and fading of some grass species, water resources pollution with organic matter, and sanitary problems caused by increase and dissemination of endo and ectoparasites (Silva, 2000).

2.1.5 Relevant problems in the in the Riacho Fundo basin, according to stakeholders

The Brazilian Federal Law 9.433/1997 defines the Water Basin Committee as the *locus* for water resources management at the local level (Salles, 2001). These Committees are parliament-like organizations of representatives from the government, the civil society and productive sectors. The Committees have the responsibility of planning, implementing, monitoring and evaluating water resources use in their area of activities.

In 2000 a group started the procedures for the creation of the Paranoá Lake Water Basin Committee. Within this group, the Riacho Fundo sub - committee has been one of the most active (Salles, 2001). This group of stakeholders identified the following as the most relevant problems in the Paranoá Lake basin and the Riacho Fundo area:

(1) Uncontrolled land occupation, changing natural and rural areas into urban areas;
(2) Problems with basic sanitation (including sewage disposal into the drainage network, in farms and water bodies);
(3) Deforestation and destruction of natural vegetation, including riparian forests;
(4) Unsustainable management techniques used by farmers (fire for deforestation; agricultural pollution with pesticides and fertilizers; cattle being raised free, out of farms; contamination of water bodies by the runoff in agricultural areas;
(5) Unsustainable management techniques used by industrial sector (detritus and effluents introduced into water bodies);
(6) Incomplete, inadequate or absent governmental actions;
(7) Deficit in community collaboration and participation (lack of knowledge about local degradation processes, of environmental concern and of mobilization).

Nowadays, stakeholders in the Riacho Fundo are highly motivated to reduce environmental damage, to clean rivers, springs and streams, and to protect the cerrado biodiversity. They are also motivated to create the Water Basin Committee in the Paranoá Lake basin, with a sub-committee in the Riacho Fundo. Qualitative reasoning models produced by the Naturnet-Redime project will support the Committee members in understanding problems and finding solutions for this region.

2.2 Goals to be achieved with qualitative models in the Riacho Fundo basin

Taking the stakeholders needs mentioned above as initial reference, we aim at the development of qualitative models

- to improve understanding of environmental systems and problems that may affect sustainability in the basin;
- to demonstrate the effects of human actions, both positively and negatively influencing different aspects of the Riacho Fundo basin system;
- to support communication between stakeholders, modellers and the public;
- to provide support for students of different levels to learn about sustainability.

2.3 Riacho Fundo basin water basin concept map

The models are meant to represent the effects of human actions on the sustainability of the Riacho Fundo basin. Therefore, the role of human society becomes central to the models. Going into more details, the goal is to represent the Riacho Fundo system structure as a set of entities and the relations between them. This structure shall become the basis for representing different situations identified in the Riacho Fundo basin. The concept map with a general view of sustainability in the Riacho Fundo basin is shown in Figure 2.

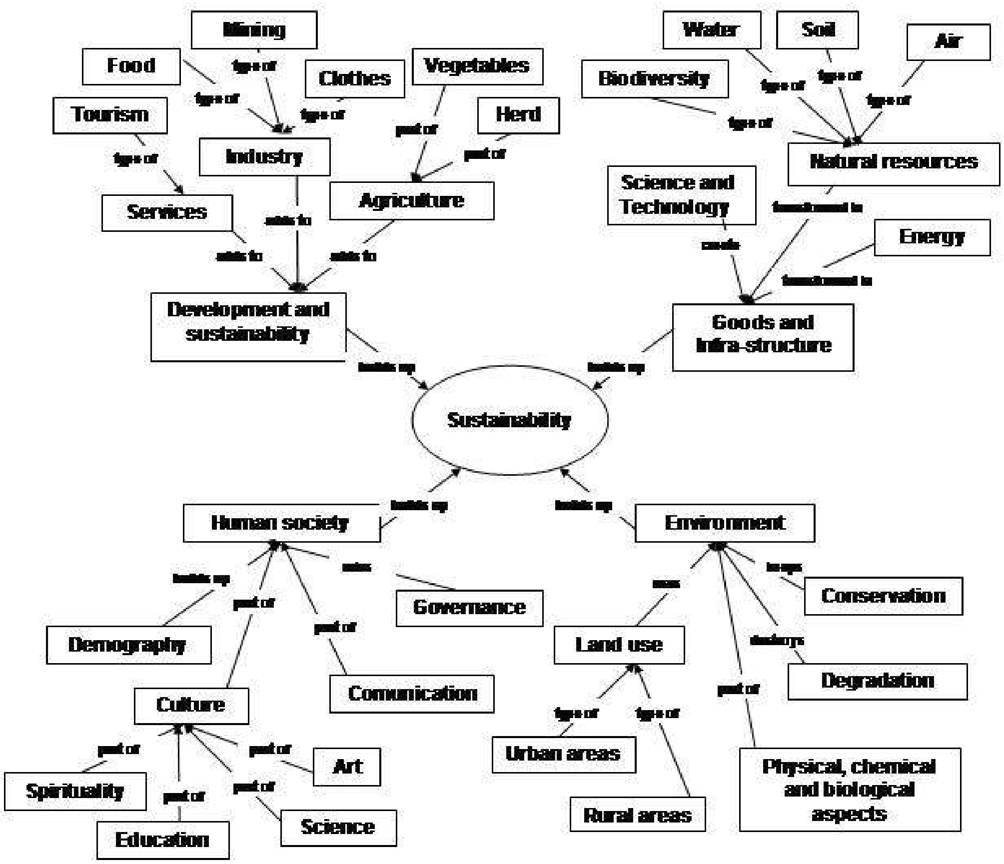

Figure 2. Concept map for the Riacho Fundo system.

3 Initial specification of the Riacho Fundo basin case study

3.1 System structure

3.1.1 Riacho Fundo system structure

From the concept map presented above, we abstract some object and relations to build up what would be a structural representation for the Riacho Fundo basin system. This structure is shown in the diagram below.

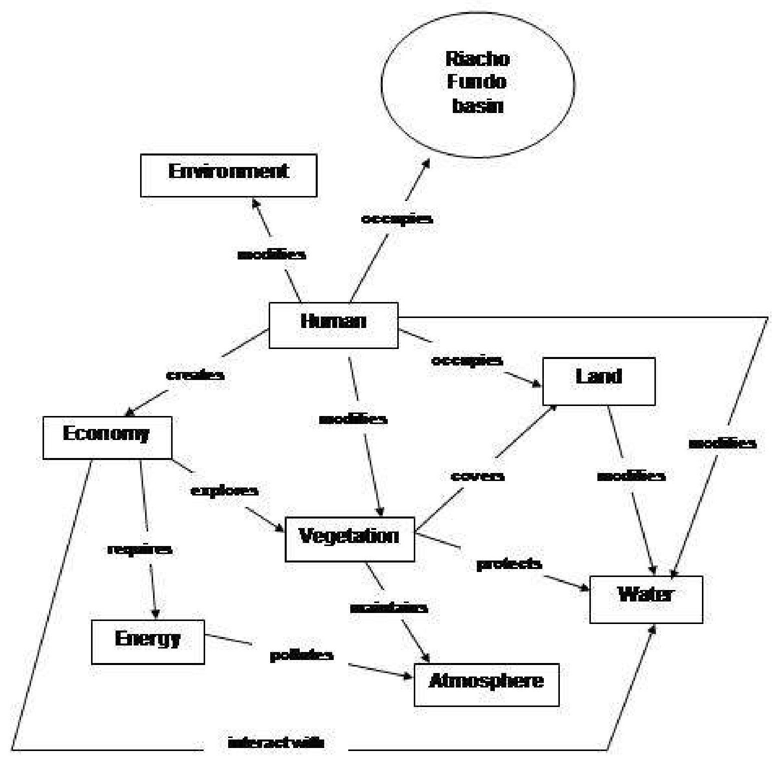

Figure 3. System structure for the Riacho Fundo system.

3.1.2 Defining entities

The most relevant concepts included in the maps are represented as entities in the models: ‘Human’, ‘Land’, ‘Atmosphere’, ‘Environment’, ‘Energy’, ‘Vegetation’, ‘Water’ and ‘Economy’:

- ***Human*** may represent human society and human actors. In this document, only human actors are represented. In this sense, entity ‘Human’ has a number of subtypes: Farmer; Businessmen; Stakeholder; Industrial; Ecologist.

- ***Land*** is related to the uses of the land. Entities represented in the models can be, therefore: Urban; Conservation; Rural.

- ***Environment*** represents a set of general environmental factors that can be further decomposed in other entities: Soil; Climate; Pollution; Biological resources; Fire; Air; Water.

- ***Vegetation*** is one of the most important elements for knowledge representation. Changes in the vegetation cover have strong impacts in terrestrial ecosystems, and removal of natural cover is often associated to major land uses. ‘Vegetation’ has subtypes representing main types in the Riacho Fundo basin and were categorized as follows: Cerrado; Forest (with the subtype Riparian); Anthropogenic.

- ***Water*** refers to water bodies observed in the Riacho Fundo system. Accordingly, the general entity Water bodies has subtypes to represent surface and underground classes. The latter is divided into River (with the subtype Stream) and Spring.

- ***Energy*** represents an important input for all human activities and is responsible for heavy changes in the environment. Means for obtaining energy are also source of environmental pollution, particularly for the atmosphere. Energy can be of two types: Renewable and Non-renewable.

Subtype entities inherit properties of their supertypes. For example, demographic attributes of ‘Human’ are inherited by Farmer, and spatial attributes of ‘Land’ are inherited by ‘Rural’ land. This way, a more specific system structure can be made, exploring farming activities.

3.1.3 Structural relationship

The structural model presented in Figure 3 is used as starting point for the modelling effort . Entities contained in the boxes are related to other entities. Accordingly, configurations between them are the labels in the arrows. An initial list of entities and configurations is presented below. If new entities are to be included in the models, new configurations may be required.

Human	***Occupies***	Riacho Fundo basin
Human	***Modifies***	Environment
Human	***Creates***	Economy
Human	***Occupies***	Land
Human	***Modifies***	Vegetation
Human	***Modifies***	Water
Vegetation	***Covers***	Land
Vegetation	***Protects***	Water
Vegetation	***Maintains***	Atmosphere

Figure 4. List of entities and the configurations that connect them.

The general structure described in Figure 3 can be changed into specific structures, applied to a more specific problems in the basin. In fact some specific structures applicable to farming, industry and conservation activities were produced, although they are not presented here.

3.2 System environment and external influences

The system environment is defined, for the model conceptualization, by the geographical limits of the water basin. When the basin interacts with relevant elements of the system environment, they would be considered as <u>external</u> influences. It is the case, for instance, of concepts such as 'Climate', 'Governance', 'Degradation', 'Conservation', and ' Economic activities'. These forces drive the outcomes of the system being represented and may be associated to management actions in the basin.

'Science and technology', 'Culture' and 'Education' may be included in further development of the models about the Riacho Fundo, particularly when influences from societal responses to sustainability problems are relevant for understanding the system or for explaining management actions. Some external factors may also be considered irrelevant for the initial modelling effort. For example, in the Riacho Fundo basin system described above no features could be associated with art and spiritual aspects. Also, at this point communication was not included in the models, although its importance for interactions of the modellers among themselves and with the public is evident.

3.3 Assumptions concerning structure

(a) Vegetation maintains the level of aggregated particles, which allows for water infiltration and permanence in the soil. In this case, the water cannot erode the land. In an area covered by a dense vegetation, torrent strength is weak, even when the torrent is already formed. However, in situations with a low proportion of trees and a high proportion of grasses, as found in anthropogenic changed Cerrados, the torrent keeps its strength. The model assumes that there is no torrent in areas covered with trees.

(b) Urban areas have a very low permeability of soil, even in towns with unpaved roads and green areas. Models should assume that infiltration is always low in urban areas.

(c) The cerrado soil is poor in nutrients and its depth is relatively small. Accordingly, this soil is particularly limited for agriculture and it is susceptible to erosion. It is assumed that natural areas have high capacity of recovering while anthropogenic changed areas have low capacity.

(d) In the urban area, the garbage disposal is inadequate and its collection, insufficient. It is assumed that there are always garbage related problems in urban areas.

4 Global behaviour

In this section, the global behaviour of Riacho Fundo case study is discussed. Three causal models are presented, in order to address the most relevant problems identified by stakeholders in the Paranoá Lake basin and the Riacho Fundo area, mentioned in section 2.5.1.

4.1 Defining processes

Six types of processes are defined, according to the principal entity involved: water; air; soil; biological; energy; human. They are presented below in tables in which most of the processes, relevant entities, main quantities, that is, rates (r) and state variables (sv), their effects and conditions for the processes start and stop are mentioned.

4.1.1 Water processes

Name	**Entities**	**Quantities (rate/state var)**	**Effect**	**Start/Stop conditions**
Water flow	- Water (underground) - Land (conservation)	- Water flow (r) - Water volume (sv) - Functional springs (sv)	This process refers to the springs of the river. The underground water flows from the soil, usually in a conservation land. This process is responsible for increasing the amount of water in the river (basin).	In normal conditions, this process is always active, only stopping if there isn't underground water anymore.
Rainfall	- Environment (climate) - Water (superficial)	- Rain (r) - Water volume (sv)	Rain water falls over the entire basin, rising all the water body levels. Rainy periods are characteristic for each region or climate. In the Riacho Fundo there are two half year seasons, rainy and dry.	This process can be represented either as the action of an agent or as an exogenous quantity, with (annual) seasonal behaviour.
Infiltration	- Water (underground) - Land	- Infiltration (r) - Water volume (sv)	The infiltration of rain water in the soil, added to the underground water. Rain and permeable land are conditions	It is reduced in urban areas as the floor becomes impermeable.
Torrent	-Water (superficial) - Land	- Torrent flow (r) - Torrent (sv) - Water volume (sv)	Rain water that does not infiltrate in the soil goes down towards the river bed. Raging torrents after heavy rains carry many types of materials such as garbage, pollutants and big things (e.g. sofas, cars). Torrent increases erosion and is bigger in land without vegetation cover.	Torrent starts during the rain and stops when the all the water rain flow into the river or other water bodies.

4.1.2 Land (Soil) processes

Name	Entities	Quantities (rate/sv)	Effect	Start/Stop conditions
Erosion	Land	- Erosion rate (r) - Soil particles (sv) - Organic matter (sv)	Process of soil and organic matter removal, followed by transportation of the material to lower areas of the basin, as the river bed. It is strongly associated to deforestated areas, and diminishes soil fertility and stability.	It is a natural process that always happens, in small quantity. However, it is stronger if the land has no vegetation cover and the area is steep . Land protection and covering with plants may stop the process.
Nutrient Adsorption	Land; Environment; Vegetation; Human	- Adsorption (r) - Available nutrients (sv)	Addition of nutrients to the land occurs after biomass or manure decomposition. It raises or at least keeps the soil fertile.	It is strongly reduced in deforested areas, specially under unsustainable management techniques. Having some vegetation is a condition for nutrient adsorption.
Aggregation	Land; Economic activity; Environment	- Aggregation rate (r) - Aggregated of particles (sv)	Process of adhesion of soil particles due to size, physical characteristics, presence of water. It can be modified (increased or decreased) due to human activity (urbanization or plough) or increased by animal trample/tread. As a result, water infiltration and vegetation rooting is diminished.	Start and stop conditions of this process are related to physical characteristics of each soil type.

4.1.3 Biological processes

Name	Entities	Quantities (rate/sv)	Effect	Start/Stop conditions
Population Growth	Vegetation; Human; Environment (other living beings)	- Population growth rate (r) - Population size (sv)	Increasing in the population size of a species, measured as biomass, stored energy or number of individuals. It is an aggregate of natality, mortality, immigration and emigration.	Physiological factors may determine natality and mortality. Migratory movements may be spontaneous or motivated by environmental conditions.
Substance production	Vegetation; Human; Environment (other living beings)	- Substance production rate (mzp) - Substance concentration (sv)	Living beings produce substances – as metabolites (biochemical sub-products); protection substances (toxins; poisons; medicines) and storage (starch) – that can have positive or negative effects in other species.	Physiological factors define start and stop conditions, often related to environmental factors.

4.1.4 Human processes

Name	Entities	Quantities (rate/sv)	Effect	Start/Stop conditions
Deforestation	Human; Vegetation; Land	- Deforestation rate (r) - Area without vegetation (sv) - Vegetation cover (sv)	It is the removal of natural vegetation of the basin by humans. It can influence the size of plant and animal populations and (or) the area covered by plants (trees and shrubs).	Human actions associated to agriculture or urbanization. Economics and population growth often are motivation for starting the process, and legislation may control or stop it.
Drainage control	- Human; - Water	- Control (r) - Controlled drained water (sv).	Drainage is related to water flow within the basin, and is particularly problematic if there is no vegetation cover or in urban areas. The torrent may cause erosion and carry garbage and other materials.	Constructing and improving the pluvial drainage system in urban or rural areas. Starts with the construction of this system by humans. Stops without maintenance.

4.2 External influences

Some of the most important external influences discussed in Section 3.2 are included in the causal models presented here. Some processes are considered the result of actions performed by agents, because they are not directly related to the main elements of the Riacho Fundo biological, physical and chemical processes. Some examples are presented below:

- Climate affects many factors, such as rainfall, a strong influence on water volume;
- Farmers can plough the soil, diminishing the particle aggregation of the soil;
- Farmers or urban population may compact the soil (using heavy machines or step on it);
- Farmers or urban population can burn natural vegetation to start agricultural activities or building houses and urbanization;
- Large animals (usually mammals) can trample/tread the ground when their population becomes bigger than the local support capacity; for instance, in the Riacho Fundo capybaras in disturbed conservation areas or free cattle in a small farms may aggregate the soil;
- Science and technology could interfere in many points of the system with the purpose to maintain agriculture production or environmental recovering (erosion, pollution);
- Governance – implementation of laws and rules intending to control erosion or deforestation.

4.3 *Causal models*

Unplanned human occupation of the Riacho Fundo basin and deforestation of large areas leads to the disappearance of many springs. Increased water consumption due to economic activities (irrigation and industrial uses), associated to sediment deposition in the river bed – due to erosion and drainage problems – creates a picture of degradation of water resources. Decreasing of water volume and water flow, associated with garbage carried out by the water facilitate contamination of the water used for irrigation of vegetables consumed in the Federal District.

Three causal models are presented here to illustrate the situation: the first one explores spring formation and drying up; the second one is about drainage and the consequences of torrent dragging materials in a urban area, and the last one represents erosion and its consequences to the land. Note that some processes defined in Section 4.1 are not included in these causal models and therefore are not explained here.

4.3.1 Spring formation

Figure 04 shows the causal model for the disappearance or maintenance of functional springs. When the springs die, the river is in real danger. Many springs of Riacho Fundo have already disappeared, but nowadays the bedside is partially protected as conservation areas.

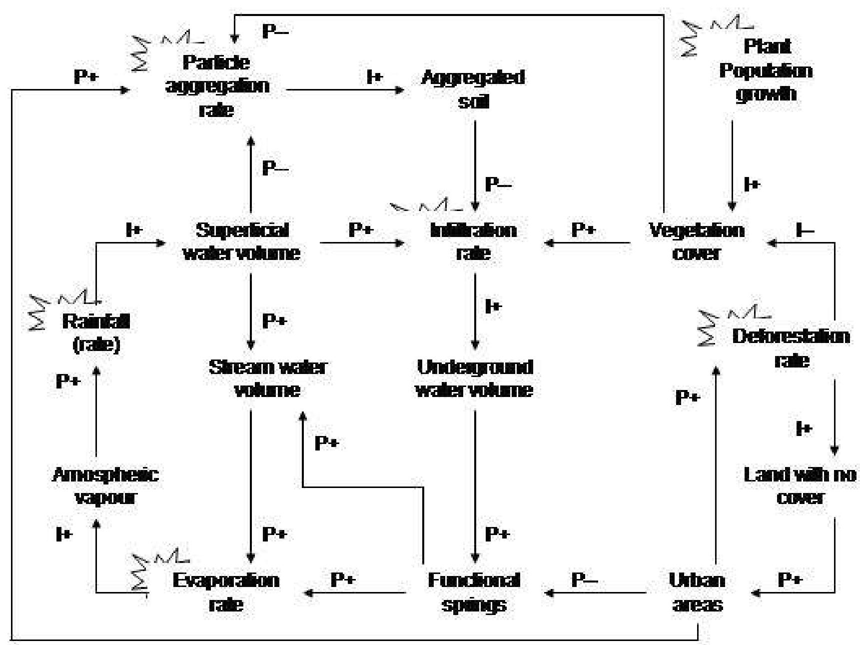

Figure 04. Springs formation causal model.

The relations shown in Figure 04 causal model read as follows:

- If the process of aggregation of soil particles is active, and the aggregation rate is negative, it causes the aggregated soil to decrease; then there is a I+ relation between these quantities.
- If aggregated soil decreases, then infiltration rate will increase because spaces between particles become bigger (more molecules of water can pass through soil particles and also they are less attracted by electric charges in soil molecules); there is a P- relation between them.
- If vegetation cover increases, then infiltration rate increases too (P+) because vegetal roots keep or diminish soil compactation.
- If there is a positive infiltration rate, the amount of water will increase the water volume at the underground; therefore there is a I+ relation between them.
- If water volume in the underground increases, the number of functional springs increases too (P+).
- If functional springs increases, then stream water volume increases too (P+) because water flows from functional springs into river beds.
- If water volume in streams increases, then the evaporation rate also increases (P+).
- If functional springs increases, then evaporation rate increases (P+) because there is more water to evaporate.
- If evaporation rate is positive and the process is active, it will cause the atmospheric vapour to increase (I+).
- If atmospheric vapour increases, the rainfall rate also increases (P+).
- If the rainfall rate is positive, and the process is active, then it causes the superficial water volume to increase (I+).
- If the superficial water volume increases, the infiltration rate increases too (P+) because there is more water to infiltrate. Note that there is a feedback loop here, which is part of the water cycle.
- If there is a deforestation rate, this amount is added on to the area without vegetation, which will increase. Therefore there is a I+ relation between them.
- If there is a deforestation rate, this amount is subtracted from the area with vegetation cover, which in turn will decrease. Therefore there is a I- relation between them. Note that there are two competing influences (deforestation rate and vegetation growth) on vegetation cover, which can increase or decrease.
- I If there is a positive deforestation rate, it causes the quantity land with no cover to increase (P+).
- I If land with no cover is increasing, then urban areas increases as well (P+), because people use that are for new settlements.
- If urban areas increases, then the number of functional springs decrease, due to soil compactation (P-). Note that this influence on functional springs competes with underground water volume. As a result, functional springs can either increase or decrease, depending on the stronger influence.
- If urban areas increases, then the particle aggregation rate increases as well (P+), because people, cars and buildings cause more soil particles to become aggregated along the time.

4.3.2 Urban drainage

Figure 05 shows the causal model for the urban drainage system and torrent dragging. When the drainage system is bad, the torrent becomes big, resulting in flooded areas, pathogen boom and soil and garbage accumulation downwards in the neighbour river. This situation occurs all over the urban areas in the Riacho Fundo basin. Different types of domestic and industrial garbage can be found in the river bed. In addition most of the areas have only few meters of riparian vegetation or just do not have it at all.

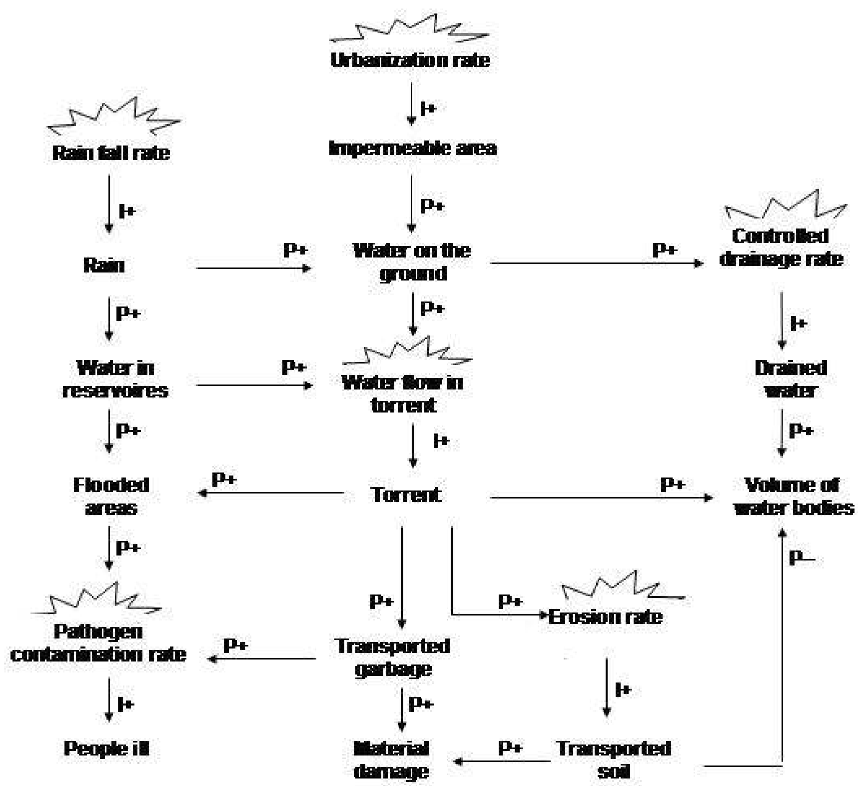

Figure 05. Land drainage causal model

The relations shown in the causal model above can be described as follows:

- If rainfall rate is positive (it is raining a certain volume of water per time), it will be added to the amount of rain, causing it to increase. Then there is a I+ relation between them.
- If the amount of rain is increasing, the volume of water in the ground is also increasing; threrefore a P+ relation exists between these two quantities.
- If urbanization rate is positive, it will cause the impermeable area to increase (I+).
- If impermeable area is increasing, the water on the ground also increases (P+).
- If rainfall rate is positive, it will be added to the water in reservoires, causing it to increase (I+).

- If water on the ground is increasing, the water flow in torrent rate increases (P+).
- If water in reservoires is increasing, the water flow in torrent rate increases (P+).
- If the water flow in torrent rate is postive and the process is active, then the torrent start to increase (I+).
- If torrent is increasing, the transported garbage increases too (P+), because the torrent strength is stronger than the garbage weight.
- If torrent is increasing, the volume of water bodies increases too (P+).
- If torrent is increasing, the flooded areas increase too (P+).
- If water in reservoires is increasing, flooded areas increase too (P+).
- If the quantity flooded areas is increasing, the pathogen contamination rate is increasing too (P+), because wet conditions favour individual growth and reproduction of most types of living beings, including those that harm human health.
- If transported garbage is increasing, the pathogen contamination rate is increasing too (P+), because garbage carries microrganisms that affect human health.
- If pathogen contamination rate is positive, it is added to the amount of people ill and this quantity will increase. Therefore there is a I+ relation between them.
- If the amount of transported garbage is increasing, the material damage in urban areas increases too (P+).
- If torrent is increasing, the erosion rate also increases (P+) because the water flow carries out soil particles.
- If the erosion rate is positive and this process is active, its value is added to the amount of transported soil and this quantity starts to increase; thus there is a I+ relation between the two quantities.
- If transported soil is decreasing, volume of water bodies drecreases (P-).
- If there is a water flow in torrent, it will be added to the amount of torrent and this quantity will increase. Therefore there is a I+ relation between them.
- If the water on the ground is increasing, controlled drainage rate increases too (P+).
- If controlled drainage rate is positive and the process of controlling drainage in urban areas exist, the it causes the volume of drained water to increase. Thus, there is a I+ relation between them.
- If the volume of drained water is increasing, then the volume of water bodies increases too (P+), because drained water normally is directed to water bodies. Note that there are three competing influences on the latter, and the outcome depends on the strenght of these influences.

4.3.3 Erosion

The causal model presented in Figure 06 shows the consequences of soil erosion to the basin. Particles and organic matter are removed from the soil and carried to the stream. The soil becomes unstable and unfertile, imposing limits to agriculture, human population growth and to the environment recovery. Functioning of the river system is hampered by the soil carried into it.

In the Riacho Fundo basin, erosion became so strong that some buildings are at collapse risk, available area for agricultural exploitation is smaller, and the river has lost some meters of its depth. It is important to notice that the expression “Riacho Fundo” translates into English as “deep stream”.

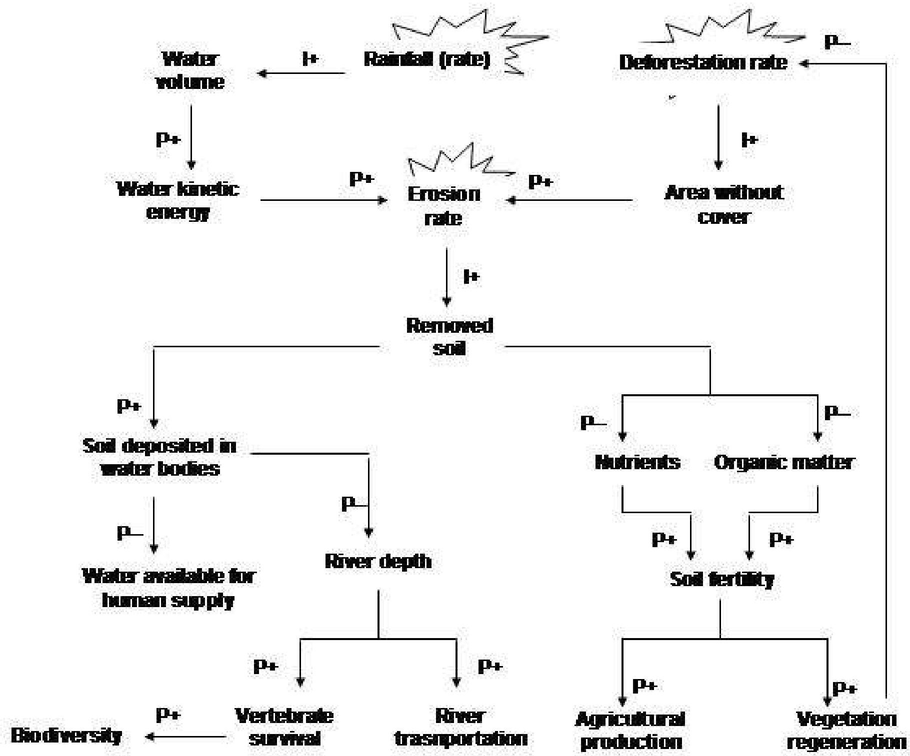

Figure 06. Erosion and its consequences causal model.

Some of the relations shown in the erosion causal model above can be described as follows:

- If rainfall exists, then the processes is active and there is a I+ relation between the rainfall and the water volume, causing it to increase due to accumulation of water on soil surface.
- If water volume increases, kinetic energy of moving water increases too; then there is a P+ relation between these quantities.
- If deforestation rate is positive and this process is active, it causes the area without vegetation cover to increase and there is a I+ relation between these quantities.
- If kinetic energy of moving water increases, the erosion rate increases too; therefore there is a P+ relation between them.
- If the area without vegetation cover increases, the erosion rate increases too (P+).
- If erosion rate is positive, the erosion process is active, so there is a I+ relation and the amount of removed soil increases.
- If the amount of removed soil increases, the amount of soil deposit in water bodies increases too (P+).
- If the amount of soil deposit in water bodies increases, water available for human supply decreases; therefore there is a P- relation between them.
- If the amount of soil deposit in water bodies increases, river depth decreases (P-).
- If the river depth decreases, river transportation decreases too, then there is a P+ relation between them.
- If river depth decreases, large vertebrates survival capacity inside the stream decreases too (P+), because their habitat becomes shallow, with less resources

available, and it may become below their needs for life maintainance.

- If the vertebrate maintenance capacity decreases, river biodiversity decreases too, then there is a P+ relation between them
- If the amount of removed soil increases, the amount of nutrients in the soil decreases (P-).
- If the amount of removed soil increases, the amount of organic matter in the soil decreases (P-).
- If the amount of organic matter in the land decreases, soil fertility decreases too; therefore there is a P+ relation between them.
- If the amount of available nutrients decreases, soil fertility decreases too, then there is a P+ relation between them.
- If soil fertility decreases, agricultural production decreases too, a notion captured by a P+ relation between them.
- If soil fertility decreases, vegetation regeneration decreases too, then there is a P+ relation between them.
- If the vegetation regeneration decreases, it activates the deforestation process and deforestation rate increases; therefore there is a P- relation between these two quantities, establishing a feedback loop.

5 Detailed system structure and behaviour: entities; attributes, configurations

5.1 Structure details

5.1.1 Entities overview

The entity subtype hierarchy for the Riacho Fundo basin is based on the structure shown in Section 3.1. The list below summarizes the most relevant entities that can be foreseen for this case study. However, this has to be changed to make the Riacho Fundo compatible with the other case studies in the NNR project.

Entity

- Human
    - Farmer
    - Urbanite
    - Ecologist
    - Businessman
    - Industrial
- Land
    - Urban
    - Rural
    - Conservation
- Environment
    - Soil
    - Water
    - Air
    - Fire
    - Climate
    - Pollution
    - Biological resources
        - Animal
        - Plant
        - Fungi
        - Monera (bacteria)
        - Protozoa
- Vegetation
    - Cerrado
    - Forest (includes Riparian)
    - Anthropogenic
- Water
    - Water bodies
        - Underground water
        - Superficial water
            - River
              Stream
            - Spring

- Energy
    - Renewable energy
    - Non-renewable energy

Figure 7. Entities of Riacho Fundo basin system structure and their subtypes.

5.2 Agents

Some agents that may be included in the models are presented below.

- Climate agent
    - Rainfall is the most evident climatic factor, increasing the volume of water bodies;
- Human agent
    - Farmers can plough the soil, diminishing the particle aggregation of the soil;
    - Farmers *or* urban population can compact the soil (tractor use in farmland or urbanization);
    - Farmers or urban population can burn natural vegetation to start sowing (to plant) or house building;
    - Governance creates laws and rules against erosion and deforestation.
- Animal agent
    - Large animals (usually mammals) can trample/tread when their population becomes bigger than the local support capacity and compact the soil. For instance, capybaras in a disturbed area or free cattle in small farms.
- Economy
    - Science and technology products and processes could interfere in many points of the Riacho Fundo models with the purpose, for example, of exploring natural resources, maintaining agricultural production or environmental recovery;
    - Engineering activities may interfere in many points of the three models with the purpose, for example, of drying up wet areas for urbanisation, improving the drainage system or controlling erosion.

5.3 Assumptions

Some of the assumptions used for model implementation are the following:

- Springs causal model
    - In the scenario “human occupation”, the aggregation rate is positive.

- Urban drainage causal model
    - Transported garbage and material damage are assumed to be qualitatively equal in order to reduce the size of the state graph.

- The cerrado soil is poor in nutrients and cannot reach their maximum levels, unless “science and technology” is present.
- In the urban area, garbage transported by the torrent cannot be zero.

- Erosion causal model
  - Particles and organic matter values in the soil are assumed to be equal in order to reduce the size of the state graph.
  - The same for river transportation and vertebrate survival capacity.
  - The same for agriculture production and (plant) population growth.

5.4 Quantities and quantity spaces

State variables are defined and modified by the processes explained in section 4:

- Aggregated soil: level of compactness of the soil;
- Vegetation cover: area of land covered by vegetation;
- Land with no cover or Area without cover: area without vegetation due to deforestation;
- Torrent: material carried out by the water in the torrent;
- Superficial water volume or Rain or Water volume: volume of water that reaches the ground due to rainfall;
- Underground water volume: volume of water in underground water bodies;
- Atmospheric vapour: water gas in the air;
- Impermeable area: area of land where the surface is impermeble;
- Drained water: volume of water carried out by a controlled drainage system;
- People ill: number mof persons contaminated by pathogens;
- Transported soil: or Removed soilmount of soil carried out by water or air due to erosion process;

Intermediate variables are quantities influenced by quantities other than rates:

- Stream water volume: volume of water contained in streams;
- Functional springs: number of functioning springs;
- Urban areas: area occupied by urban settlements;
- Water in reservoires: volume of water in rivers, streams and man-made reservoires;
- Water on the ground: volume of water in the surface of the ground, water that did not infiltrate;
- Flooded areas: number and area occupied by land that became under water;
- Volume of water bodies: volume of water in all the water bodies;
- Transported garbage: Garbage carried by the torrent;
- Material damage. Damage to the human materials such as infra-structure, constructions or productive settings;
- Soil deposited in water bodies: soil that become sediment in water bodies;
- Water available for human supply: volument of good quality water for human use;
- River depth: profundity of river or streams;
- River transportation: transportation of passengers and goods in rivers;
- Vertebrate survival: medium and large species of fish (carp), reptiles (alligator, tortoise and snakes), mammals and other aquatic vertebrates;
- Fertility: nutrient and organic matter available for plants;
- Biodiversity: in the context of this model, diversity of animal species and communities;

- Agricultural production: includes vegetables and crop production and husbrandry.
- Vegetation regeneration: vegetation growth, recovering areas that have been deforestated.

The following table presents the quantities and their respective quantity spaces.

Type	Quantity	Quantity Space
State Variables		
	Aggregated soil	low, medium, aggregated
	Vegetation cover	zero, small, medium, large
	Land with no cover (Area without cover)	small, medium, large
	Torrent	zero, small, medium, large
	Superficial water volume (Rain,Water volume)	zero, small, medium, large
	Underground water volume	small, medium, large
	Atmospheric vapour	small, medium, large
	Impermeable area	zero, small, medium, large
	Drained water	zero, low, medium, high, total
	People ill	zero, small, medium, large
	Transported soil	small, medium, large
Intermediate Variables		
	Stream water volume	zero, small, medium, large
	Functional springs	zero, small, medium, large
	Urban areas	zero, small, medium, large
	Water in reservoires	zero, small, medium, large
	Water on the ground	zero, small, medium, large
	Flooded areas	zero, small, medium, large
	Volume of water bodies	small, medium, large
	Transported garbage	zero, small, medium, large
	Material damage	zero, small, medium, large
	Soil deposited in water bodies	small, medium, large
	Water avilable for human supply	small, medium, large
	River depth	small, medium, large
	River transportation	zero, small, medium, large
	Vertebrate survival	zero, small, medium, large
	Fertility	small, medium, large
	Biodiversity	zero, small, medium, large
	Agricultural production	zero, small, medium, large
	Vegetation regeneration	
Rates		
	Particle aggregation rate	minus, zero, plus
	Rainfall	zero, plus
	Infiltration rate	minus, zero, plus
	Population growth rate (human, plant, pathogen)	minus, zero, plus
	Deforestation rate	zero, plus
	Evaporation rate	zero, plus
	Erosion rate	zero, plus
	Urbanization rate	zero, plus
	Controlled drainage rate	zero, plus

5.5 Description of scenarios and system behaviour

5.5.1 Drying of springs

Two situations involving the drying up of springs are modelled:

- The first one is a positive scenario of springs in a conservation area. It is assumed that there are no humans removing the vegetation or degrading the water resources. In this case, the number functional springs increases.
- The second scenario refers to an area under the process of human occupation, which provides a negative perspective. Aggregation rate is positive, infiltration decreases, and the number of functional springs is reduced.

Springs rasing in conservation area

In this scenario, Deforestation rate and Particle aggregation rate have value zero. All quantities start in their lowest values. The system behaviour is presented in the table below.

State	Values and (in) equalities	Description
1	Particle aggregation rate < 0, and soil state is aggregated; vegetation cover increasing; superficial water volume is increasing.	Starting with a condition in which the soil is not very favourable for the number of springs to increase, other factors allow for an increase in the infiltration process. Eventually it reaches the number of functional springs.
2	Particle aggregation rate < 0, refinforced by the vegetation cover that is increasing, and soil aggregation state = medium; superficial water volume is increasing.	The infiltration process rate increases faster due to a decrease in the degree of particle aggregation, increasing the underground water volume.
3	Particle aggregation rate < 0, and vegetal cover is increasing; particle aggregation state = low; superficial water volume is increasing.	The infiltration process rate increases faster due to a decrease in the degree of particle aggregation, increasing the underground water volume and the number of functional springs reach the maximum value.

Table 1. System behaviour for the “Springs raising in conservation area” scenario.

Springs fading due to human occupation

In this scenario,urban areas increase and cause deforestation rate to increase. Deforestation rate is greater than plant population growth and Particle aggregation rate has value plus. There is no rainfall. All other quantities start with intermediate values.

State	Values and (in) Equalities	Description
1	Deforestation rate > Population growth (Vegetation); Particle aggregation rate is plus; Rainfall and Infiltration rate have value zero	Human occupation leads to deforestation and soil aggregation. This is a situation in which deforestation is greater than plant vegetation growth and there is no rain. In that area, number of functional springs is medium.
2	Deforestation rate > Population growth (Vegetation); Vegetation cover has value <medium, dec>; Particle aggregation rate is <plus, inc>; Rainfall has value zero and Infiltration rate assumes value minus. Water flow (underground) assumes value minus. Functional springs has value <small, decreasing>	Influenced by particle aggregation state (increasing) and vegetation cover (decreasing), Infiltration rate has value minus. This value propagates to underground water and to functional springs, which starts decreasing.
3	The inequalities and values in state 2 remain and functional springs assumes value zero.	Without rain and infiltration, functional springs reaching value zero, water volume in the stream no longer receives influence and tends to stay stable. Other influences may reduce the stream volume.

Table 2. System behaviour for the “Springs fading due to human occupation” scenario.

5.5.2 Urban drainage

One scenario is modelled to represent aspects related to urban drainage:

- Urban area without a drainage system, so the torrent will be positive and river sedimentation due to transported soil, great material damage and a boom of pathogenic organisms contamination occur.

Urban area increasing

Typically urbanization rate is increasing and rainfall is positive. Water volume in reservoirs and on the ground are stable. Other quantities such as controlled drained water, water flow in torrent, torrent, transported garbage, material damage, flooded area, pathogen contamination rate, and people ill have value zero.

State	Values and (in) Equalities	Description
1	Impermeable area assumes derivative positive. Rainfall has value plus and Water on the ground has derivative positive. Torrent drag assumes value plus; torrent, transported garbage, material damage and flooded area	Without control on drainage and rain increasing the amount of water at the surface, with no control on water drained, the rate of water movement (water flow in torrent) receives influences and becomes active. The

	assume value small. Pathogen contamination rate assumes value plus; and people ill assumes value small.	effect of this process propagates to all the other quantities which start increasing.
2	Water on the ground continues increasing and this propagates to other quantities, such as torrent, transported garbage, material damage, flooded areas and people ill area have value medium.	If the conditions do not change and the processes continue active, the values of all the quantities mentioned keep increasing.
3	Water on the ground, torrent, transported garbage, material damage, flooded areas and people ill area have value large.	The most important end state in this simulation shows the worse effects of urbanization with no drainage system: river pollution, pathogen contamination and material damage.

Table 3. System behaviour for the "Urban area increasing" scenario.

5.5.3 Erosion

One scenario is modelled to represent consequences of the erosion process:

- Erosion always occurs. In the causal model presented in Figure 6 the erosion process is influenced by water kinetic energy and area with vegetation cover. Rainfall and deforestation rate are active. River transportation, fertility, agriculture production and biodiversity go down. The decreasing capacity of vegetation regeneation reduces the recovering capacity of the entire ecosystem.

Erosion plus

State	Values and (in) Equalities	Description
1	Rainfall = plus; deforestation rate = plus; erosion rate = plus; removed soil = small and increasing. Water supply, river depth, river transportation, vertebrate survival, biodiversity, nutrients, organic matter have value large and is decreasing. Fertility, agricultural production and vegetation regeneration have value large, decreasing.	With the erosion process being active, its effects propagate to the rest of the system. Initially three quantities are affected: Particles are removed from the soil and are sent to water bodies, nutrients and organic matter start decreasing. As consequences of these changes, water supply, fertility, agriculture and the vegetation are also affected.
2	Rainfall = plus; deforestation rate = plus; erosion rate = plus; removed soil = medium and increasing. Water supply, river depth, river transportation, vertebrate survival, biodiversity, nutrients, organic matter have value large and is decreasing. Fertility, agricultural production and vegetation regeneration now have value medium and are decreasing.	As the conditions remain constant, the negative effects of erosion continue to affect the quantities in the system and worsening the situation.

3	Rainfall = plus; deforestation rate = plus; erosion rate = plus; removed soil = large and keeps increasing. Water supply, river depth, river transportation, vertebrate survival, biodiversity, nutrients, organic matter have value large and is decreasing. Fertility, agricultural production and vegetation regeneration now have value small and are still decreasing.	The worse results of the erosion are presented in this end state: drastic reduction of water supply, river transportation and agricultural production. Biodiversity is lost.

Table 4. System behaviour for the “Erosion plus” scenario.

5.6 Detailed description of model fragments

5.6.1 Springs formation model

A. Process fragments

1. Soil particles aggregation

This model fragment describes a natural process that occurs in land, the aggregation of particles, and has three children model fragments, described below.

Conditions:
Entity Land

Consequences:
Particle aggregation rate **I+** Aggregated soil.

1.a Compacting

The effect of human occupation on soil compaction is defined in this model fragment:

Conditions:
Active assumption “human occupation”

Consequences:
“Particle aggregation rate” has value plus

1.b No aggregation

This model fragment models the situation in which the soil is not being aggregated.

Conditions:
Active assumption “no aggregation”

Consequences:
“Particle aggregation rate” has value zero

1.c Disaggregation

This model fragment describes the influence of science and technology on soil aggregation.

Conditions:
Active assumption “efficient techniques”

Consequences:
“Particle aggregation rate” has value minus

2. Infiltration

The infiltration process is responsible for increasing the water volume in the underground soil.

Conditions:
Superficial Water *wets* Soil
Soil *contains* Underground water

Consequences:
Infiltration rate (Superficial Water) **I+** Underground water volume (Soil)

3. Evaporation

This model fragment shows how atmospheric water vapour is formed. This model fragment has a child shown below.

Conditions:
Air *contains* Water

Consequences:
Evaporation rate (Air) **I+** Atmospheric vapour (Water)

3.a Evaporation inactive

The activity of evaporation is totally dependent of functional springs and of stream water volume. This model fragment captures this knowledge.

Conditions:
Functional springs has value zero
Stream water volume has value zero

Consequences:
Evaporation rate has value zero.

4. Deforestation increases open landscape

The notion that deforestation reduces the area covered by vegetation and increases the area without vegetation is captured in this model fragment.

Conditions:
Human *occupies* Land

Consequences:
Deforestation rate (Human) **I+** Land with no cover (Land)

5. Deforestation reduces vegetation cover

Deforestation has another influence, on the area covered with vegetation. This is captured in this model fragment.

Conditions:
Human *occupies* Land
Vegetation *covers* Land

Consequences:
Deforestation rate (Human) **I-** Vegetation cover (Land)

6. Rainfall increases superficial water

This model fragment describes changes in the water volume at soil surface due to the influence of an external agent, the climate.

Conditions:
Climate *modifies* Superficial Water

Consequences:
Rainfall (Climate) **I+** Water volume (Superficial Water)

B. Static fragments

1. Influences on infiltration

This model fragment shows that the infiltration rate receives influences from three state variables (Water volume; Particle aggregation state; Vegetal convering).

Conditions:
Superficial Water *wets* Soil
Soil *contains* Underground water
Vegetation *covers* Land

Consequences:
Aggregated soil (Soil) **P-** Infiltration rate (Superficial Water)
Superficial water volume (Soil) **P+** Infiltration (Superficial Water)
Vegetation cover (Land) **P+** Infiltration (Superficial Water)

2. Influences on the aggregation process

This model fragment captures the idea that particle aggregation rate receives influences from urban areas, water and vegetation.

Conditions:
Land *contains* Superficial water
Vegetation *covers* Land

Consequences:
Urban areas (Land) **P+** Particle aggregation rate (Land)
Superficial water volume (Water) **P–** Particle aggregation rate (Land)
Vegetation cover (Land) **P–** Particle aggregation rate (Land)

3. Springs feed the stream

This model fragment shows that functional springs are the most important source of water for a river.

Conditions:
Spring *feeds* Stream

Consequences:
Functional springs (Spring) **P+** Stream water volume (Stream)

4. Springs feed evaporation

This model fragment shows that functional springs influences the evaporation process.

Conditions:
Air *contains* Water

Consequences:
Functional springs (Spring) **P+** Stream water volume (Stream)

5.6.2 Urban drainage model

A. Process fragments

1. Urbanization

This model fragment shows that urbanization influences the permeability of the soil.

Conditions:
Human *occupies* Land

Consequences:
Urbanization rate (Human) **I+** Impermeable area (Land)

2. Control of drainage

Governmental activities are essential for improving the drainage system. This model fragment shows that control on drainage determines the amount of water that will be directed to the stream and reduces the torrent drag. This model fragment has a child shown below.

Conditions:
Human *modifies* Water
Active assumption “Government action”

Consequences:
Controlled drainage rate (Human) **I+** Drained water (Water)

2.a Child: Control of water draining is zero

This child model fragment defines a specific situation: if there is no drainage system and the control on water is zero, then the drained water is also zero.

Conditions:
Drainage control has value zero

Consequences:
Controlled drained rate has value zero.

3. Pathogen contamination

Conditions:
Human *modifies* Biological resources (with label Pathogens)
Human *modifies* Water
Pathogen contamination rate value is greater than zero

Consequences:
Pathogen contamination rate (Pathogens) **I+** People ill (Water).

4. Torrent

This model fragment defines how torrent works.

Conditions:
Entity Water

Consequences:
Water flow in torrent **I+** Torrent

5. Erosion

This model fragment defines how erosion works.

Conditions:
Entity Soil

Consequences:
Erosion rate **I+** Transported soil

B. Static fragments

1. Torrent rate value

The water flow in torrent is influenced by two different factors (quantities). In this fragment they are presented together.

Conditions:
Land *modifies* Water
Land *modifies* Superficial Water

Consequences:
Water on the ground (Superficial water) **P+** Water flow in torrent (Water)
Water in reservoires (Water) **P+** Water flow in torrent (Water)

2. Consequences of water being moved

Conditions:
Human *occupies* Land
Human *modifies* Water

Consequences:
Torrent (Water) **P+** Flooded areas (Land)
Torrent (Water) **P+** Transported garbage (Water)
Torrent (Water) **P+** Small and big particles (Water)
Torrent (Water) **P+** Erosion (Land)

3. Influences on the pathogen contamination rate

This model fragment captures one of the most important consequences of torrents in urban areas: water contamination. Here the influences on the process rate are presented.

Conditions:
Human *modifies* Pathogens
Human *occupies* Land

Consequences:
Transported garbage (Human) **P+** Pathogen contamination rate (Human)
Flooded areas (Land) **P+** Pathogen contamination rate (Human)

4. Material damages caused by transported garbage

Material damage caused by the torrent are presented in this model fragment, with a definition of correspondence between transported garbage and material damage, so that they assume equal values:

Conditions:
Human *modifies* Water
Human *occupies* Land

Consequences:
Transported garbage (Water) **P+** Material damage (Human)
Transported soil (Land) **P+** Material damage (Human)
Directed correspondence (Transported garbage, Material damage).

4. Erosion affects water bodies

This model fragment shows that transported soil influences the volume of water bodies.

Conditions:
Human *modifies* Water
Human *occupies* Land

Consequences:
Transported soil (Land) **P+** Volume of water bodies (Water)

4. Rainfall affects volume of water bodies

This model fragment shows influences from rain on the volume of water bodies.

Conditions:

Climate *modifies* Water bodies

Consequences:

Rain (Climate) **P+** Water on the ground (Water)
Rain (Climate) **P+** Water in reservoires (Water)

C. Agent model fragment

1. Rainfall

Rainfall increases the water volume in soil surface and at the stream.

The conditions for this fragment are the entities water and land and the configuration “wets”. In this fragment, Water volume is linked to the entities Land and Water. Water volume is positively influenced at the soil surface (Land) and at the Stream (Water). Two labels, superficial and stream, can be added to specify that the rain water falls *on* the soil (Land) and in the river in this model.

Conditions:

Entity Climate

Consequences:

Rainfall **I+** Rain

5.6.3 Erosion model

A. Process fragments

1. Deforestation increases open landscape

The notion that deforestation increases the area without vegetation is captured in this model fragment.

Conditions:

Human *occupies* Land

Consequences:

Deforestation rate (Human) **I+** Area without cover (Land)

2. Erosion effects

This is an important model fragment, because it establishes direct influences of the erosion process.

Conditions:
Land

Consequences:
Erosion rate (Land) **I+** Removed soil (Land)

B. Static fragments

1. Kinetic energy of the water

This model fragment implements the influence of the volume of water on the kinetic energy.

Conditions:
Entity Water

Consequences:
Water volume (Water) **I+** Water kinetic energy (Water)

2. Effects of the removed soil by erosion

This model fragment explicits the influences of erosion on the water, nutrients and organic matter.

Conditions:
Soil *modifies* Water

Consequences:
Removed soil (Soil) **P+** Soil deposited in water bodies (Water)
Removed soil (Soil) **P–** Nutrients (Soil)
Removed soil (Soil) **P–** Organic matter (Soil)

3. Consequences of erosion on humans and rivers

This model fragment explicits the influences of erosion on the water, nutrients and organic matter.

Conditions:
Soil *modifies* Water

Consequences:
Soil deposited in water bodies (Water) **P–** Water available for human supply
Soil deposited in water bodies (Water) **P–** River depth (Water)

4. Impacts of changes on river profundity

This model fragment shows indirect influences of erosion on transportation and biodiversity.

Conditions:

Water *affects* Human
Water *modifies* Biological resources

Consequences:

River depth (Water) **P+** River transportation (Human)
River depth (Water) **P+** Vertebrate survival (Biological Resources)

5. Influences on soil fertility

This model fragement captures the determinants of soil fertility.

Conditions:

Entity Soil

Consequences:

Nutrients (Soil) **P+** Soil fertility (Soil)
Organic matter (Soil) **P+** Soil fertility (Soil)

6. Effects of soil fertility

This model fragment shows the consequences of erosion in factors influenced by fertility.

Conditions:

Human *modifies* Soil
Vegetation *covers* Soil

Consequences:

Soil fertility (Soil) **P+** Agricultural production (Human)
Soil fertility (Soil) **P+** Vegetation regeneration (Vegetation)

7. Erosion and biodiversity

This model fragment establishes the relation between depth of the stream and the river transport and animal survival, which in turn influences biodiversity.

Conditions:

Environment *includes* Biological Resources

Consequences:

Vertebrate survival (Biological Resources) **P+** Biodiversity (Environment)

C. Agent model fragment

1. Rainfall

Rainfall increases the water volume in soil surface and at the stream.

The conditions for this fragment are the entities water and land and the configuration “wets”. In this fragment, Water volume is linked to the entities Land and Water. Water volume is positively influenced at the soil surface (Land) and at the Stream (Water). Two labels, superficial and stream, can be added to specify that the rain water falls *on* the soil (Land) and in the river in this model.

Conditions:
Climate

Consequences:
Rainfall **I+** Rain

6 Conclusions

This document presents a textual description of the model to be developed about the Riacho Fundo case study, focusing on basic biological, physical, and chemical processes related to environmental sustainability. Irregular occupation has promoted a number of negative impacts on the environment: loss of biodiversity and erosion are among the most important. Based on the stakeholders opinion about the most important problems in the basin, some general objectives were set for this modelling effort, mainly related to improving understanding of structure and behaviour in Riacho Fundo systems, demonstrating the effects of human actions and supporting communication about these problems.

A concept map was developed in order to represent relevant aspects for sustainability of the Riacho Fundo basin. Eight entities were identified: 'Human, 'Land', 'Atmosphere', 'Environment', 'Energy', 'Vegetation', 'Water' and 'Economy'. These entities were productively organized in a hierarchical way, so that inheritance of properties allows for reuse of the system structure in different models. The concept map was very effective in capturing the main ideas that could organize the problems mentioned by the stakeholders. The concept map was then used to guide the identification of the most important problems, and drove the choice of issues to be modelled. We discussed three models: springs formation, urban drainage and erosion.

A classification of processes according to the main entity types was created and allowed for inclusion of the most relevant causal determinants of the Riacho Fundo system behaviour: water processes, land (soil) processes, energy processes, air processes, biological processes and human processes. Most of the relevant aspects of sustainable development of the Riacho Fundo case study can be represented this way. Exploring the subtype hierarchy of entities, the same basic system structure can be used to represent different economic activities, such as farming, industry and conservation.

The development of the model fragments pointed out to some possible extentions for the initial modelling effort. However, some changes are expected for the implementation stage, due to technical reasons or because some improvements are necessary for better representing aspects of the complex Riacho Fundo basin system.

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