A Garp3 model of environmental sustainability in the River Mesta (Bulgaria)

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Abstract

We present a qualitative model of sustainable development issues in the River Mesta, Bulgaria. Following a standardized framework for conceptual description of QR case studies, we have organized our expert knowledge about biological and physical processes in the stream as well as impacts of external influences like pollution, erosion, and water abstraction. We present essential background about the modelled system, and describe how available knowledge was encapsulated into QR knowledge structures including model fragments and scenarios. Finally, we present simulation output based on this knowledge and discuss how this output contributes to understanding factors affecting sustainability of the River Mesta system.

Introduction

To realize the European Union's Strategey for Sustainable Development (SSD; European Commission 2001), citizens must become more educated about factors that affect sustainable development (SD). Qualitative reasoning (QR) has proven effective in educational settings as a means to educate about cause and effect ({Bredeweg, 2003 #4184}). This paper contributes to the objectives of the SSD, in the context of the NaturNet-Redime project, by presenting a QR model about an SD case study. This QR model will become part of a curriculum aimed at teaching concepts of sustainability, including the impacts of biological, physical, and chemical processes on human well-being (Nuttle et al. 2006).

The basic objective of this modelling project is to transfer expert knowledge (contained in a QR model) about processes affecting sustainability to stakeholders, decision makers, and citizens. This paper builds from Uzunov (2006), which presented preliminary progress in organizing qualitative knowledge about the River Mesta system using a "structured approach to qualitative modelling" (Bredeweg et al., in press). Here, we update that information based on the actual content of the implemented model. We begin by presenting essential background on the River Mesta system and a list of model goals. Next, we describe the most and insightful model fragments and scenarios that contribute to fulfilling these goals. We then present simulation results based on these scenarios, highlighting the most relevant behaviour paths. Finally, we discuss how these simulation results contribute to our model goals, in the context of supporting the SSD's educational objectives.

Model System

Varadinova (2006) describes the basic features of the River Mesta. The region is recognized as economically under-developed, with high unemployment. Regional development plans focus on intensifying economic activities based mostly on natural features of the region. This includes further development and diversification of tourism; modernizing and intensifying agriculture and forestry; increasing energy production from hydropower; construction of new roads and streets, and enhancing infrastructure like sewage systems, wastewater treatment plants, and domestic waste landfills.

All of these activities need more water than the River Mesta watershed can supply, potentially leading to conflicts between users. State and local authorities are faced with difficult solutions how meet these competing demands. Reconciliation of these conflicts requires finding of sustainable solutions and appropriate environmental and/or ecosystem health indicators, in addition to the economic and/or social ones usually taken into account.

One of the indicative parameters of aquatic ecosystem health is the amount of dissolved oxygen (DO) in the water. Oxygen is an essential component for all living organisms in the aquatic ecosystem. All water bodies contain some amount of DO due to diffusion from the atmosphere. Normally there is a dynamic equilibrium between inputs and outputs of DO due to the biological processes of oxygen production and consumption. Water pollution, abstraction, erosion and other human activities can disrupt this balance, worsening ecosystem health and decreasing sustainable uses of ecosystem services.

Based on these factors, being able to discriminate between anthropogenic and natural fluctuations of DO is potentially of great importance for decision making about sustainable and integrated management of aquatic ecosystems. QR provides a modelling paradigm that allows explicit representation of the various processes that interact in a water body to affect DO (Bredeweg and Struss 2003). Furthermore, the ontology provided by QR facilitates education about these processes, which will be useful for explanation to decision makers and stakeholders—those people who have a vested interest in the outcome of sustainable decisions.

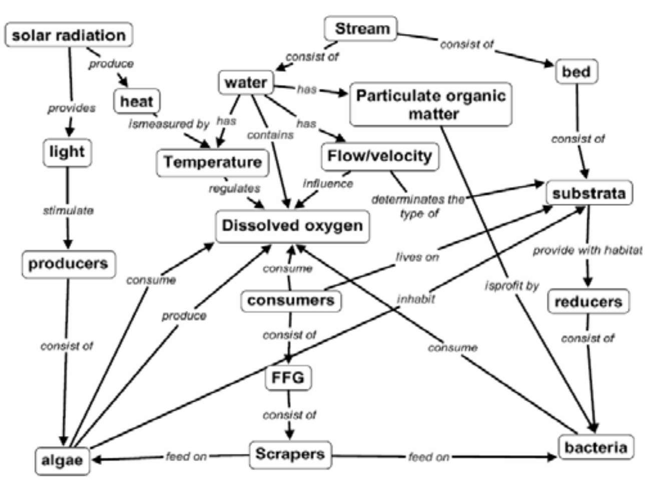

Figure 1. River Mesta concept map

Model Specification

Main Model Goals

We have identified the following modelling goals to focus and narrow the scope of our model. The model should:

1. Describe the behaviour of DO under different conditions (hydro-morphological, physico-chemical and biological).
2. Examine mechanisms of change in ecological functions anthropogenic influences of organic pollution, erosion (due to agriculture and deforestation), and water abstraction.
3. Be useful for scientific and management purposes to explain cause and effect processes to decision makers and stakeholders.

Although the focus of the model is the River Mesta system, the processes should be generalisable to any riverine aquatic ecosystem.

Concept Map

We begin with a concept map that helps identify, clarify, and focus our knowledge about the system of interest (Figure 1). Two main groups of processes influence DO. Physical processes involve solar radiation which provides light and heat, as well as water itself which modify the hydro-morphology of the channel (depth, width, bottom substrata, etc.), thus providing living organisms with habitats. Biological processes involve three groups of organisms responsible for oxygen production (producers: algae) and oxygen consumption (consumers and reducers). All aquatic organisms consume oxygen for their respiration.

Global Behaviour

Here, we identify and describe the main causal processes and how these combine to form the full causal model of the system as well as describe typical scenarios and expected outcomes. These textual descriptions help organize our knowledge for later implementation using QR dependencies.

Main Internal Processes

Oxygen diffusion is a physical process that involves the entity *water*, which has quantities *Temperature*, *DO*, *Light intensity*, and *Heat amount.* This describes the dependence of DO on the water temperature. The lower the temperature, the more oxygen can be held by the water. The process is always active while any water body is above freezing (between 0 and 100 C), which is always true for the River Mesta. The oxygen content within a small, turbulent stream is approximately at or near saturation. DO decreases following warming of water downstream and during summer. Discharges of thermal pollution (effluents of cooling waters from thermal plants for energy production and other industries) may reduce DO substantially in streams and rivers.

Aeration is a physical process that involves the entity *water* and the quantities *DO* and *Flow velocity.* Diffusion of oxygen from the air is facilitated by the turbulent movement of water. This turbulence mixes air and water and thus increases the amount of oxygen dissolved from these mixture. Turbulence is higher when flow velocity is higher and also in shallow water.

River bed substrata is a physical process that involves the entities *Stream*, *Water*, *River Bed*, and *Substrata* with the quantities *Flow velocity* and *Size of substrata particles* (stones/gravel). The kinetic energy of running water modifies the river bed's composition. The higher current velocity, the larger sized particles form the bottom bed. Larger particles (like stones and gravel) provide more surface to be inhabited by living organisms.

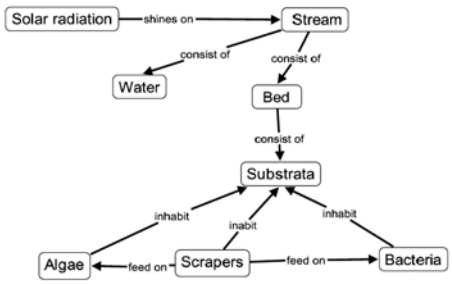

Figure 2: Structural model of the stream system

Oxygen Production is a biological process that involves entities *Light* and *Algae* and quantities *Light intensity*, *Number of algae*, *Photosynthetic rate*, and *DO*. Light from solar radiation is the primary factor for oxygen production through the process of photosynthesis by algae. Pollution and erosion due to effluents of organic and/or inorganic particles seriously reduce light penetration and thus the rate of photosynthesis.

Oxygen Consumption (respiration) is a biological process that involves all living entities (*Scrapers*, *Bacteria*, *Algae*) and the quantities *Amount of* living entities and *DO*. All aquatic organisms consume DO for their respiration thus decreasing its amount in water. Higher water temperatures accelerate the consumption rate.

Feeding (scraping/grazing) is a biological process that involves the entities *Algae*, *Bacteria*, and *Scrapers* as well the *Amount of* each. Scrapers are aquatic invertebrates that scrape (or graze) the thin layer of algae and bacteria (so called bio-film) on the surface substrata. The amount of scrapers depends on the amount and availability of their prey. The process is always active as long as food is available (algae and bacteria); it is assumed that scrapers will re-colonize as soon as food is available. Feeding is strongly and positively related to water temperature and rate of oxygen consumption. External impacts like pollution may negatively influence the process by changing the amount of the food.

Bacterial degradation is a process that involves the entities *Bacteria* and *Water* and the quantities *Amount of Bacteria*, *DO*, and *Amount of POM* (particulate organic matter). Bacterial degradation involves decomposition of organic matter from dead organisms and inputs from the watershed. The process decreases DO. The amount of bacteria depends strongly on the amount of POM in water bodies. Input of POM by urban and industrial wastewaters accelerates degradation until DO is completely exhausted.

External Influences

All pressures that originate outside the River Mesta are considered external influences. We consider three external influences that have the greatest impact on sustainability of the River Mesta.

Erosion increases the amount of suspended solids in the stream, decreasing light intensity. Erosion is created by deforestation and unsustainable agriculture. Sustainable agricultural and forestry practices reduce soil erosion.

Pollution increases POM in the stream. POM affects DO, accelerating oxygen consumption by bacteria, making it less available for scrapers and algae. The effects of pollution depend on the amount of wastewater discharge and water temperatures. POM generally arises from point sources, such as households, industries and other human activities. Hence, wastewater treatment prior to discharge into water bodies can reduce the amount of POM discharging river bodies.

Water abstraction reduces the amount of water in the stream. Humans need water for various purposes of their every-day life (drinking, washing, bathing) and many economic activities – agriculture (irrigation), industry (supply for technological processes and manufactured goods), etc. Decreasing water discharge in natural water bodies affects all physical and biological processes and thus may negatively affect ecosystem health of the River Mesta downstream the abstraction point.

Causal Model

The effects of internal and external processes are refined as causal dependencies following Qualitative Process Theory (Forbus 1984). The full causal model of the River Mesta is depicted in Figure 3. Model documentation fully describes each of the dependencies depicted in Figure 3 (Uzunov et al. 2006). We refer the reader to the textual descriptions above for explanations for each dependency.

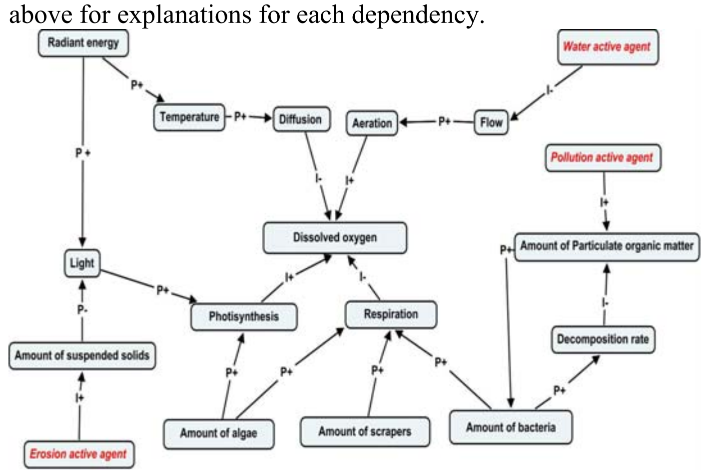

Figure 3. Causal model for the River Mesta, as implemented.

Model Implementation

A model has been implemented in the Garp3 workbench (Bredeweg et al. 2006). Implementation details contain the detailed description of the modelled system: *Entities*, *Attributes*, *Configurations* (structural relationships between Entities), *Quantities* associated to each *Entity*, *Quantity Spaces* associated to *Quantities*, *Scenarios*, *Model Fragments*, *Agents* (External influences), and *Assumptions*. The implementation phase of model development helped us clarify our thinking on several of the processes described above. Therefore, there are slight differences between the textual descriptions above and how they were implemented. Nevertheless, the basic ideas remain the same, and the description of model fragments makes clear how the processes were modelled.

Entities, Configurations, and Agents

Based on the concept map, we identified the main entities involved in dissolved oxygen balance of the River Mesta. These are organized into a type hierarchy (Figure 4) and described in Table 1.

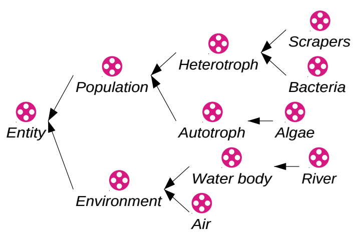

Figure 4. Entity hierarchy for the River Mesta model.

Table 1: Entities involved in the River Mesta QR model

Entity	Description
Stream	A natural water body which consists of some amount of running water and river bed/bottom.
Water	Part of the stream, a fluid that possibly contains dissolved gases and substances. Water has its flow/velocity and temperature.
River bed	The solid background within which the water runs downstream. The bed consists of different types of substrata, the size of particles of which depends on current velocity.
Algae	A kind of producer. Periphytic algae inhabit (live on) substrata (river bed).
Bacteria	Reduce the organic substances and bodies of dead organisms. They play important role in self-purification processes.
Scrapers	A functional feeding group of trophic structure of the community of bottom invertebrates (macro-zoobenthos), which feed on small-sized organisms like algae and bacteria, scrapping/grazing them from surface of the bottom substrata they used to live on.
Solar radiation	An environmental factor which is the main source of energy (light and heat) for the aquatic ecosystems.

Configurations are used to model relations between instances of entities and agents. Possible configurations include: River *consist of* Water body and River bed. Population *lives in* River bed.

External influences (described above) were organized into Agents. These include Erosion, Pollution and Water abstraction. The effects of these agents are described in the model fragments (below). Configurations specify whether a given agent is *active in* a water body.

Quantities and Quantity Spaces

We use four quantity spaces (QS) to describe the various quantities in the model. These are summarized in Table 2. The main quantity of interest, *Dissolved oxygen*, uses a QS consisting of five values. We felt this would be more insightful for demonstration and education with stakeholders, being that this is the main focal quantity. For example, the existence of riverine flora and fauna depend of DO concentration and survival rate of organisms decreases with lower DO concentration. Only some populations can survive in low DO concentration

Table 2: Quantity spaces and the quantities they are associated to (▌ indicates an interval value, ● indicates a point value).

Quantity space	Quantities	Associated Entity
‹mzp›	All derivatives	
▌plus		
●zero		
▌min		
‹vllrhvh›	*Dissolved oxygen*	Water body
▌very high		
●high		
▌regular		
●low		
▌very low		
‹zp›	*Biomass,*	Population
▌plus	*Photosynthesis;*	Algae
●zero	*Production*;	
	Respiration;	Heterotroph
	Diffusion rate,	Water body
	Aeration rate,	
	Excretion rate;	Bacteria
	Decomposition rate;	Erosion (agent)
	Soil particles;	Polluter (agent)
	Pollution;	Sun (agent)
	Solar radiation;	Water abstractor
	Water abstraction	(agent)
‹interval›	*Flow velocity, Light,*	Water body
▌interval	*Temperature, Heat,*	
	Particulate organic	
	matter;	
	Biomass	Population

(microaerobic conditions). Very low concentrations result in anaerobic conditions where only some bacterial populations can exist. Thus, being able to distinguish these qualitative values is useful for explaining consequences of certain behaviours to learners.

All "intermediate" quantities, whose behaviour is modelled mainly to show how they affect DO, but whose values are not directly of interest, use a simple QS; serving to reduce ambiguity in the simulation. Quantities that influence others via a direct influence (I+ or I-, Forbus 1984) require a known zero so it can be known whether the quantity is positive or negative. Hence, they use QS *‹zero, plus›*, or *‹zp›*. Quantities that influence via qualitative proportionalities (P+ or P-) don't require a known zero (their derivative carries the influence), so they have a QS consisting of a single interval, *‹interval›*. The exception to this rule is that quantities associated to agents use QS *‹zp›*, because we wanted to represent whether the process was active *‹plus›* or inactive *‹zero›*, even thought they act via qualitative proportionalities.

Model Fragments

As a guiding principle for organizing causal dependencies into model fragments, we viewed a water body to represent a dynamic equilibrium of positive and negative influences. For example, DO is in equilibrium between aeration and diffusion, whereas populations are in balance between production (or photosynthesis) and respiration. The prevalence of one of the processes can change the equilibrium. External influences, acting via agents, upset the equilibrium and may cause the system to establish a new lower equilibrium DO content or population size. These unsustainable and unfavourable conditions will persist unless the external influences are removed.

Another basic principle we employed is that values for quantities with only a single interval QS are set in model fragments rather than in scenarios (see e.g. Figure 5); this allows for sparser scenarios, which are clearer to communicate to stakeholders. Finally, we have constructed the model fragments using the "one concept, one model fragment" principle (Salles and Bredeweg 1997), which also helps in developing learning materials based on the model and makes the most of the capabilities of compositional modelling (Falkenhainer and Forbus 1991).

Aeration and Diffusion: These balancing processes are the main controls on DO content of a river. Figure 5 shows the *Diffusion* process model fragment (MF). It imports a model fragment *Water body* that specifies some basic information about all water bodies. The *Diffusion* MF uses a qualitative proportionality to model the fact that as *Temperature* increases, so does *Diffusion rate*. Diffusion reduces the amount of DO in a water body; thus there is a negative direct influence of *Diffusion rate* on *Dissolved oxygen*. Finally, there is a feedback (via P+) from *Dissolved oxygen* to *Diffusion rate*, because the more DO in the water, the more can diffuse out.

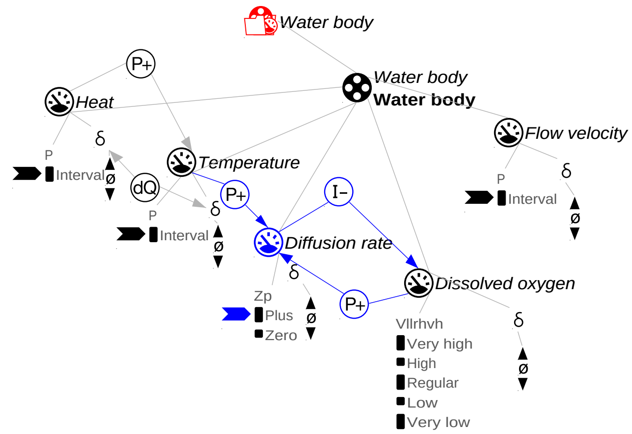

Figure 5. The diffusion process model fragment.

Aeration process MF is structurally similar to *Diffusion*. As *Flow velocity* increases, so does *Aeration rate* because the churning of turbulent water flow causes air to be incorporated into the water; this is modelled using a qualitative proportionality. Aeration causes an increase in the amount of DO; thus there is a positive direct influence (I+) from *Aeration rate* to *Dissolved oxygen.* In contrast to *Diffusion*, *Dissolved oxygen* does feed back on *Aeration.*

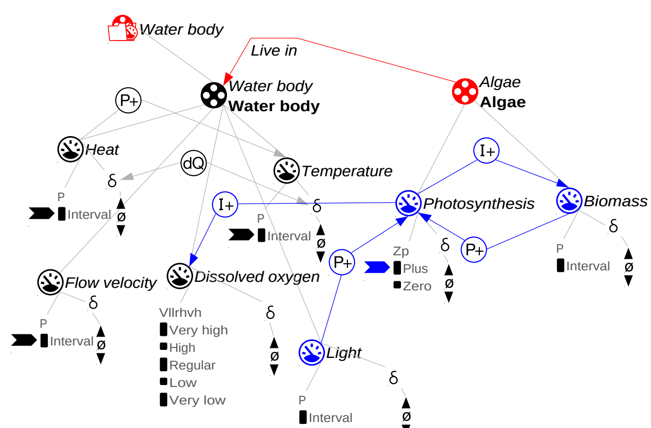

Figure 6. The photosynthesis process model fragment

Photosynthesis is another process that can add DO to a water body. The rate of *Photosynthesis* is positively proportional to both the amount of *Light* and *Biomass* of *Algae*: the more light and the more algae there are, the more photosynthesis happens. *Photosynthesis* rate increases (I+) the *Biomass* of the *Algae* and increases (I+) the amount of *Dissolved oxygen* in the water body.

Production and Respiration: The *Production* process is analogous to *Photosynthesis* except it applies to

Heterotrophs (including *Bacteria* and *Scrapers* but not *Algae*). So far, we don't specify the source of energy for the production rate, but in the future this will come from feeding on another population. Another difference is that *Production* rate does not increase *Dissolved oxygen*.

The *Respiration* process applies to any *Population* (including therefore *Algae* and *Heterotrophs*). *Respiration* rate reduces (I-) *Biomass* and Dissolved oxygen. There is a feedback (P+) from *Biomass* to *Respiration* rate.

Decomposition is a process whereby bacteria break down particulate organic matter (POM), using up DO in the process. *Bacteria* have a *Decomposition rate*, which decreases (I-) both the amount of *Particulate organic matter* and *Dissolved oxygen* in a *Water body*. There is a feedback (P+) from *Particulate organic matter* to *Decomposition rate*, so the more POM, the faster it is broken down and the faster DO decreases.

Excretion is the creation of POM from the dead bodies and excrement (in the case of scrapers) of each of the populations in a river. In one model fragment, the *Excretion rate* is positively proportional (P+) to the *Biomass* of each of these populations (*Algae, Bacteria,* and *Scrapers*). A process model fragment (*Excretion*) then specifies that *Excretion rate* increases *Particulate organic matter* in a *Water body*.

Agent model fragments: There are four agent model fragments: Erosion, Polluter, Sun, and Water abstractor. Normally, agents are implemented with rates that affect aspects of the model system via direct influences (I+ or I-). However, from our point of view, each of these processes is always active to some degree on any water body; hence, we are interested in showing how *changes* in the status quo propagate through the system to affect the DO balance of the stream. Hence, each of these agents is associated with a quantity that influences one or more of the endogenous system quantities via a qualitative proportionality. Effects of the agents are simulated when the configuration *active in(Water body, [Agent])* and the relevant quantity's derivative is specified in a scenario. The effects of the agents and their relevant quantities are:

P+(Water body: Light, Erosion: Soil particles)
P+(Water body: Particulate organic matter, Polluter: Pollution)
P+(Water body: Light, Sun: Solar radiation)
P+(Water body: Heat, Sun: Solar radiation)
P-(Water body: Flow velocity, Water abstraction: abstractor)

Scenarios

Scenarios present initial situations, including the configuration of the system of interest and starting values for quantities. We present two scenarios, each starting off with *dissolved oxygen* in the interval ‹*Regular*›. One (Scenario A) shows only how physical aspects of the system affect DO via their effects on aeration and diffusion rates (Figure 7). The other (Scenario B) shows both physical and biological effects on DO (Figure 8). In Scenario B, to reduce ambiguity, *production* and *respiration* rates start out equal for *scrapers* and *bacteria*; *photosynthesis* and *respiration* start out equal for *algae*, and *decomposition* and *excretion* rates as well as *aeration* and *diffusion* rates also start out equal.

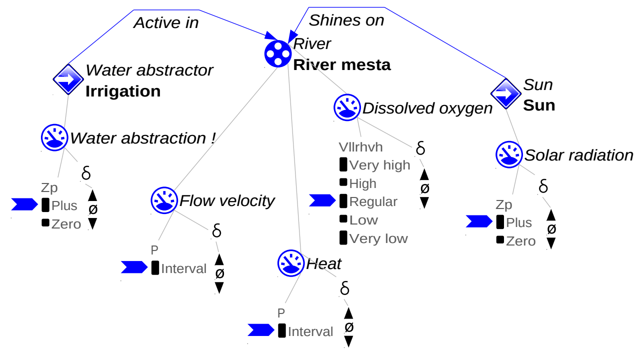

Figure 7. Scenario examining the interaction of physical processes in affecting DO of the River Mesta. Quantities associated to the agents Sun and Irrigation are set to be exogenously increasing (note exclamation marks).

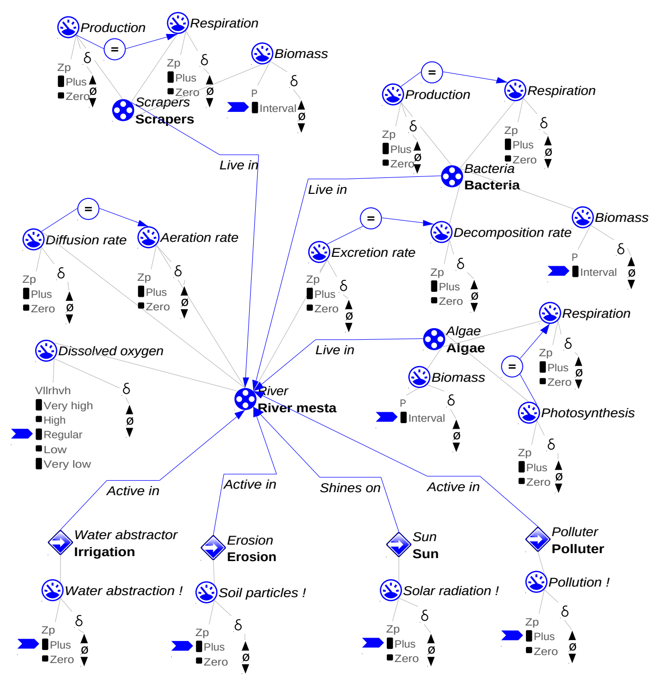

Figure 8. Scenario examining the interaction of physical and biological processes in affecting DO of the River Mesta. Quantities associated to the agent Polluter is to be exogenously increasing whereas agents Water abstracter, Sun, and Erosion are exogenously steady (note exclamation marks).

Simulation Results

Scenario A: Physical Processes

Simulation of this scenario results in five initial states (states 1 – 5, Figure 9) that represent possible interpretations of the net effects of aeration and diffusion on dissolved oxygen. Causal dependencies (Figure 10) give rise to a total of 20 possible states originating from these initial five. Figure 9 (right) presents value histories of three pathways that are representative of the behaviour that *Dissolved oxygen* may take (all states are shown in the three value histories; readers can therefore track each possible transition in the state graph). Note that for each of the value histories presented, the system may start out at any state ≤ 5 (e.g., the middle value history represents paths [5 → 9 → … → 10 → 11] as well as path [2 → 10 → 11]). In each path, *Dissolved oxygen* eventually reaches value *‹very low, -›,* even if it initially increases. The equation histories (Figure 9, bottom) make clear that this behaviour occurs due to the relative magnitudes of *Diffusion rate* and *Aeration rate*. The full causal model of all physical aspects of the system is depicted in Figure 10. Scenarios (not shown) where the agents are both exogenously decreasing result in the opposite behaviour (*Dissolved oxygen* eventually increases to *‹very high, +›*). When the agents take different behaviours (one increasing, the other decreasing or stable, etc.), then all behaviours are possible, and *Dissolved oxygen* may stabilize at any value in the QS.

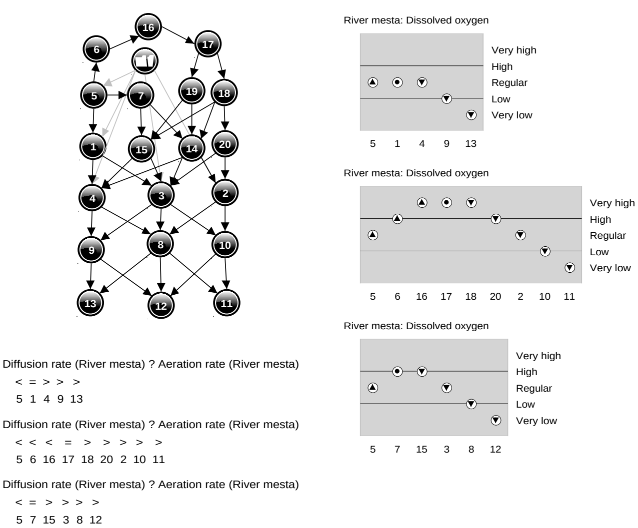

Figure 9. State graph (top left), value histories of selected paths (top right), and corresponding equation histories (bottom) for Scenario A.

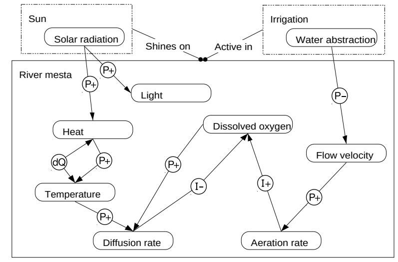

Figure 10. Causal model for Scenario A.

Scenario B: Biological and Physical Processes

Simulation of this scenario results in one initial state (Figure 11) with *Dissolved oxygen* decreasing. Causal dependencies (Figure 12) give rise to a total of 17 states in the full simulation, with 11 possible end states (Figure 11). In these end states, *Dissolved oxygen* either stabilizes at a value less than the starting value or continues to decrease in the interval *‹very low›* (see value histories, Figure 13). This happens because as *Pollution* increases, so does *Decomposition rate,* which has a negative influence on *Dissolved oxygen* (all other processes are held constant in the scenario). *Dissolved oxygen* may stabilize after initially decreasing because with less *Dissolved oxygen* in the river, *Diffusion rate* becomes less. Hence, *Dissolved oxygen* may stabilize when the combined negative influences of diffusion, decomposition, production, and respiration become equal to the combined positive influences of aeration and photosynthesis. Since none of these change except *Diffusion rate* and *Decomposition rate*, it all depends on the relative size of these two quantities.

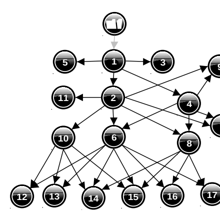

Figure 11. State graph for Scenario B.

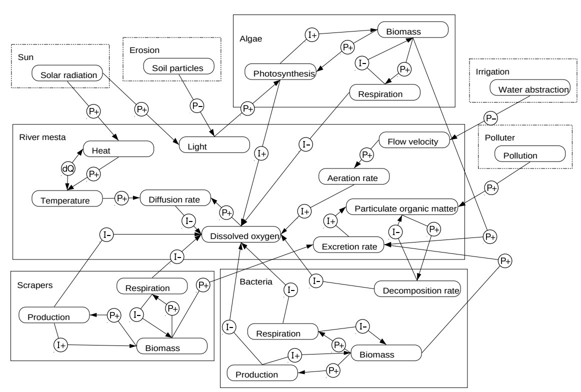

Figure 12. Causal model for Scenario B.

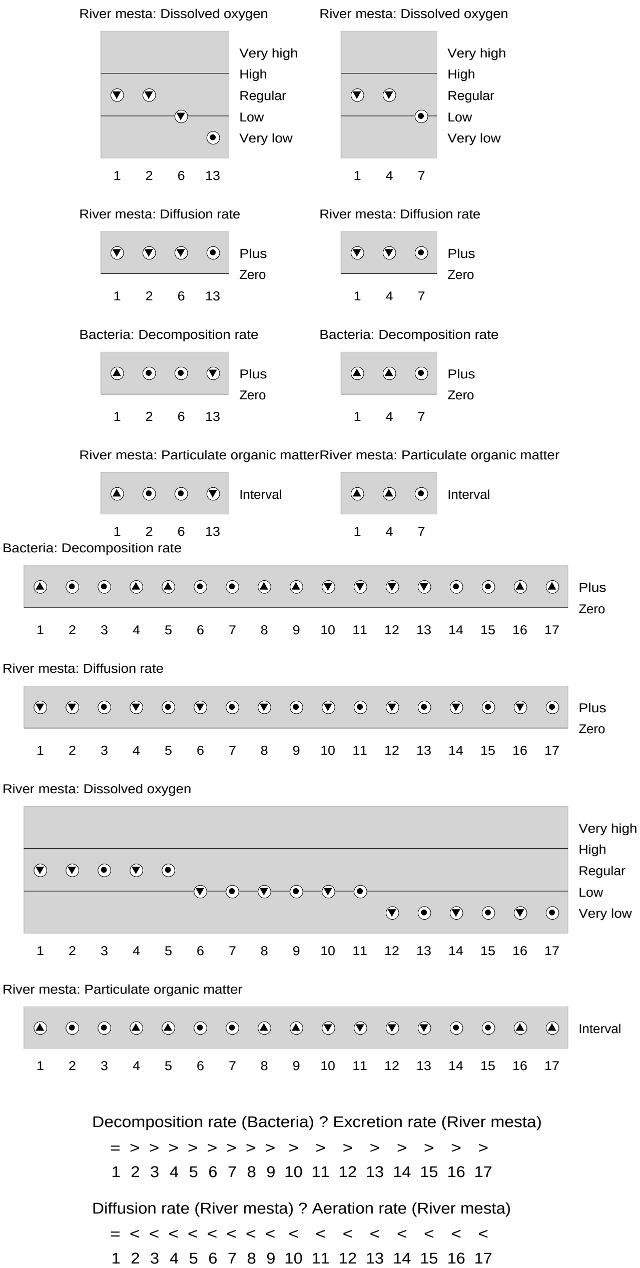

Figure 12. Value histories for two selected paths (top) and for all states in the full simulation of Scenario B (middle), showing quantities where the value may change during the simulation, as well as equation histories (bottom) for balancing processes. The two value histories at top show representative paths; other paths are variations and can be constructed from the state graph (Figure 11) and the corresponding values in the value history (middle).The value for *Pollution* is ‹*plus, +*› and all other values are either ‹*plus, 0*› or ‹*interval, 0*›, as appropriate for the quantity (see Table 2).

Conclusions

This paper has presented progress on a Garp3 model of sustainability issues in the River Mesta, Bulgaria. The model focuses on dissolved oxygen in the river as an indicator of healthy status of the river ecosystem. Since the initial model specification stage (see Nakova et al. 2006), many issues have been clarified and further refined as the ecological knowledge has been captured into the QR ontology using the Garp3 workbench.

In building this model, we employed three modelling principles that are interesting from the QR perspective. First, state variables (DO and population size) are all impacted by balanced negative and positive influences. Second, all intermediate rates are modelled with the simplest quantity space possible, either an open interval (for processes operating via qualitative proportionalities) or quantity with a point value for zero and a positive interval (for processes operating via direct influences). Finally, we employed a large quantity space for the focal quantity representing DO so that a broader range of dynamics can be visualised by users. Although these values are not assigned to quantitative landmarks, they are useful in explaining under what DO conditions certain groups of organisms can persist in the stream.

The model thus captures the most important processes directly and indirectly affecting dissolved oxygen in a river body. By employing a clear ontology for expressing balancing influences, we were able to capture the expert ecological knowledge into model fragments that are both relatively self-contained and insightful. These can be reused and assembled by the Garp3 reasoning engine to make more complex causal models of multiple populations. Further work on the model will better describe the trophic interactions among the three populations. Specifically, feeding relationships between scrapers and bacteria and between scrapers and algae need to be specified.

Once finalized, the model satisfies the first two modelling goals specified above. Concurrent work in the NaturNet-Redime project centres on developing educational materials from this and other models of other case studies to teach about issues concerning environmental sustainability (Nuttle et al. 2006) This will help us to satisfy the third goal for the model, namely to be used as a tool for decision makers and stakeholders to make more informed decisions concerning sustainable development of the River Mesta system.

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being studied in this project can be found at http://www.naturnet.org.

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