Dissolved oxygen in the River Mesta (Bulgaria): a case study for qualitative modelling of sustainable development

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Abstract

We present progress towards developing a qualitative reasoning model of sustainable development issues in the River Mesta, Bulgaria, following a standardized framework for conceptual description of QR case studies. Using the QR ontology, 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 model system, organization of this knowledge into knowledge structures that will drive our QR model, and define causal dependencies and model fragments that will be implemented in the QR modeling workbench, Garp3. This case study serves as an example of the successful use of the new framework to help compare and re-combine QR case studies of sustainability issues in the future.

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). This paper contributes to this objective in the context of the NaturNet-Redime project by presenting progress towards developing a qualitative reasoning (QR) model about a SD case study that will be integrated with other case studies (see, in part, Salles and Rios Caldas, this volume, and Cioaca et al., this volume) to develop on online curriculum to learn about causal processes that affect environmental, social, and economic factors related to SD.

Both to support the model building effort as well as to facilitate integration of the different models, Bredeweg et al. (2005; this volume) developed a "structured approach to qualitative modelling". The goal of this paper is to describe progress in following the methodology for the River Mesta, Bulgaria, case study. We also provide a critique on the effectiveness of the methodology framework for supporting development of QR models by novice QR model builders and discuss conclusions and perspectives for future work.

Model System

We focus on the River Mesta (RM), Bulgaria. Varadinova (2006) describes the basic features of the River Mesta (RM). 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 RM 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 reasoning provides a modeling paradigm that allows explicit representation of the various processes

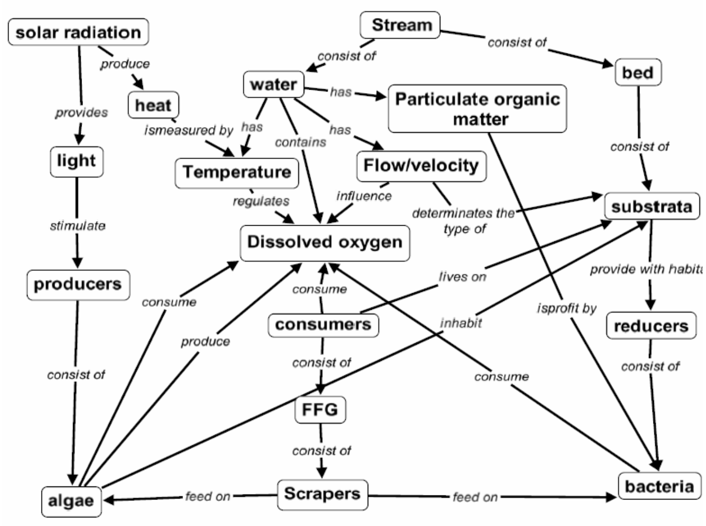

Figure 1. River Mesta concept map

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.

Main Model Goals

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

1. Describe the behavior 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 RM system, the processes should be generalizable 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.

System Selection and Structural Model

Here, based on the concept map and model goals, we identify the entities involved in the RM system (Table 1). Figure 2 depicts the structural relationships among entities graphically. These relationships pertain to entities within the RM system—we identify processes happening within the stream itself to be part of the system structure, whereas anthropogenic influences will be considered as external agents: outside the system, but influencing its behavior

Global Behavior

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 RM. 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

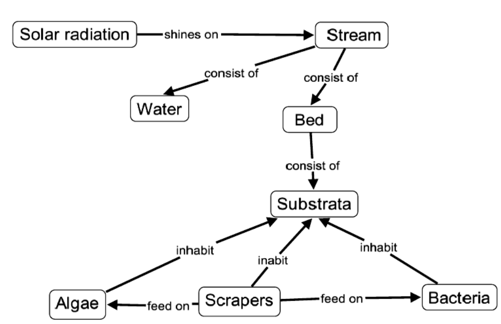

Figure 2: Structural model of the stream system

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 (macrozoobenthos), 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.

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.

Oxygen Production is a biological process that involves entities *Light* and *Algae* and quantities *Light intensity*, *Number of algae*, *Photosynhetic 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 RM are considered external influences. We consider three external influences that have the greatest impact on sustainability of the RM.

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 RM downstream the abstraction point.

Causal Model

The effects of internal and external processes are refined as causal dependencies following Qualitative Process Theory

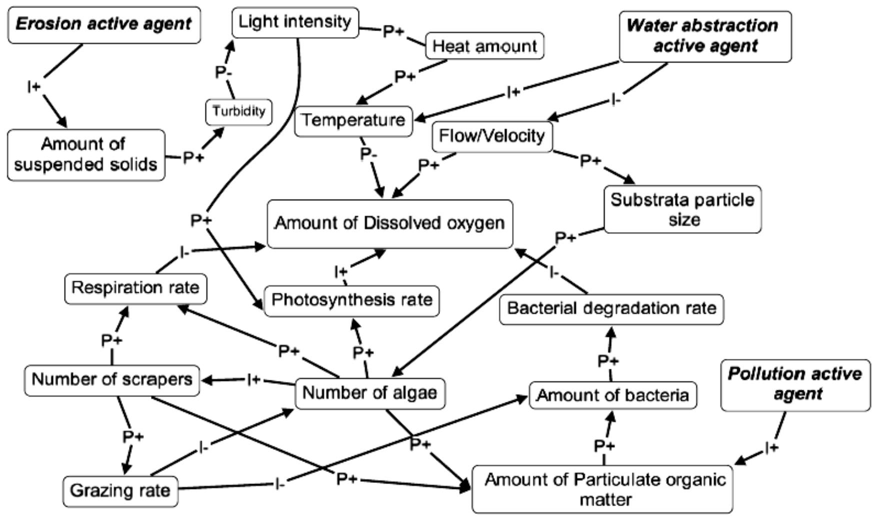

Figure 3. Causal model for the River Mesta.

(Forbus 1984). The full causal model of the RM is depicted in Figure 3. Model documentation fully describes each of the dependencies depicted in Figure 3 (Uzunov and Nakova 2006). We refer the reader to the textual descriptions above for explanations for each dependency.

Scenarios

Scenarios present initial situations, including the configuration of the system of interest and starting values for quantities. Our scenarios investigate the effects of applying and controlling the various external influences of erosion, pollution, and water abstraction. In each of these cases, we expect that dissolve oxygen in the RM will be highest in when each external influence is controlled (not active) and lowest when all external agents are active.

Detailed System Structure and Behavior

Here, we transform the graphical and textual descriptions of processes into the more explicit terminology of the Garp3 QR modelling workbench (Bredeweg et al, this volume). This includes organizing causal dependencies into model fragments, agents, assumptions, etc. For the purposes of the present paper, we describe a few of the model fragments that implement the ideas described above. These model fragments can be combined to build a 'mini-model' showing how pollution increases POM, which increase bacteria and consequently decreases DO.

Static Model Fragments. These define structural relations between entities and indicate propagation of changes from one quantity to another using proportionalities (P+ and P-). Here we provide one example.

Name: Bacterial degradation
Conditions:
Entities: *Stream, Water, Bed, Substrata, Bacteria*
Configurations: *Consist of, Inhabit,*
Consequences:
Quantities: *Amount of bacteria, Bacterial degradation rate, POM.*
Causal Dependencies: *POM propagates positively (P+) to Amount of bacteria. The amount of bacteria propagates positively (P+) to Bacterial degradation rate.*
Explanation: This model fragment refines the textual description under the section "Global behavior". It says that if there is a stream that consists of water, a bed, and substrate, and if bacteria inhabit the substrate, then there will be an amount of bacterial, a bacterial degradation rate associated to bacteria and particulate organic matter associated to water. The causal dependencies specify that if POM increases, so does the amount of bacteria and that if amount of bacteria increase, so does bacterial degradation rate.

Process Model Fragments. These describes how magnitudes of quantities cause changes to occur in other quantities via direct influences (I+ and I-). Here, we provide an example that builds from the information explicated in the static model fragment just described.

Name: Bacterial degradation process
Conditions:
Entities: *Stream, Water, Bed, Substrata, Bacteria*
Configurations: *Consist of, Inhabit,*
Consequences:
Quantities: *Bacterial degradation rate, DO*
Causal Dependencies: *Bacterial degradation rate have a negative influence (I-) to DO.*
Explanation: The conditions are as described above for the static model fragment. This model fragment describes additional consequences, namely that the

quantities bacterial degradation rate and DO will be introduced and bacterial degradation rate will negatively influence DO (so if bacterial degradation rate is positive, DO will decrease).

Agent Model Fragments. These are special process model fragments (containing direct influences, I+ and I-) that model how external influences cause changes in a system. They generally relate to processes that humans can exert some control over, as opposed to natural processes that humans generally can't or don't directly control.

Name: Pollution
Conditions:
Agent: *Pollution*
Entities involved: *Stream, Water*
Configuration: *Consist of*
Consequences:
Quantities: *Pollution active agent, POM*
Values: *Pollution active agent = positive*
Causal dependencies: *Pollution active agent have positive influence (I+) to Amount of POM*
Explanation: If the conditions *stream consist of water* hold and the agent *Pollution* is applied, then the consequences will be that a quantity *Pollution active agent* will be added to *stream*, along with *POM*. Furthermore, *Pollution active agent* will be positive and positively influence *POM* (*I+*, causing *POM* to increase).

Critique of Structured Methodology

Following the structured methodology described in Bredeweg et al (2005; this volume), we were able to organize a large amount of qualitative knowledge about stream ecology and factors affecting the RM into a manageable set of explicated ideas. The methodology allowed us access model-development expertise more efficiently than would have been possible without the framework. Nevertheless, we did experience some difficulties in implementing the methodology. One difficulty was that it was difficult for us to see how the various steps contributed to the model—the process seemed fragmented. This is perhaps due to our inexperience thinking in terms of entities, quantities, relations, etc., rather than thinking more holistically about 'everything at once', as we usually do. Additionally, more examples related to ecology would have been helpful for us to better grasp ways ecological systems can be organized into the QR ontology. For example, it was often difficult for us to distinguish whether a concept was best captured as an entity or quantity. Also, we sometimes had difficulty determining the proper use of qualitative proportionalities (P+/P-) and direct influences (I+/I-).

Conclusions

The next phase of our research involves implementing the ideas presented here into the Garp3 workbench. An advantage of using the structured methodology is that it enforces a structure to the model development process, making it easier to compare and contrast the various case studies (see Salles et al and Cioaca et al, this volume). This structure also facilitates the task of extracting essential commonalities between models to develop an integrated library of reusable QR model fragments that can be reassembled to investigate other situations in other systems related to their sustainability, contributing to our goals of developing QR models that can educate about a wide variety of SD issues and situations.

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