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Qualitative models about stream ecosystem recovery: Exploratory studies

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ABSTRACT

Most of water ecosystems are endangered by human actions, in spite of their importance for all living systems. Qualitative models and simulations may be useful for stream ecosystem recovery in many ways: for understanding such systems, to predict values of variables and to combine such understanding with restoration and proactive management. However, building qualitative models puts new challenges both for qualitative reasoning and ecological modelling research. This study describes the development of qualitative models and simulations about the effects of pollution by organic matter and its consequences on the amount of dissolved oxygen and mortality of fish. We present simulations of effective and ineffective management practices, which may result in increasing and reducing fish stocks. Problems we found and solutions we implemented during the modelling effort are discussed, including the explicit representation of assumptions and the role of ambiguities in the outcomes of the models. Developing qualitative theories for water ecology will require a better understanding of the basic processes, such as photosynthesis and respiration. These complex processes are related to both energy flow and nutrient cycling, and have impact on different parts of the whole ecosystem. We argue that new ontologies and qualitative domain theories will be required in order to tackle these complex interactions between physical, chemical and biological phenomena observed in water systems.

1. Introduction

Rivers and other water bodies are complex systems of interest all over the world because they suffer from damage caused by human actions, despite their recognized importance for all living systems. Rivers present, from the headwaters to their mouth, a continuous gradient of changing environmental conditions. This gradient can be associated to a *continuum* of biotic adjustments and typical communities are formed. One of the most accepted frameworks for integrating physical and biological features of river systems concerning their structure, function and stability is the River Continuum Concept (Vannote et al., 1980).

Based on energy equilibrium theories, this concept assumes that producer and consumer communities become established in harmony with the dynamic physical conditions of the channel. Taking into account the river size (smaller in the head and bigger in the mouth) and the balance between production and consumption of organic matter and biological energy, three different regions are identified: headwaters, medium-sized streams and large rivers. Headwater streams depend on the input of organic matter from terrestrial ecosys-

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tems and local production of biomass is low. Using the ratio gross primary production (total photosynthesis) to respiration (*P*/*R*) as an indicator, headwater streams are characterized by $P/R<1$. As stream size increases, the reduced importance of terrestrial organic matter input coincides with enhanced primary production by algae and rooted vascular plants. The conditions in medium sized rivers can therefore be described as $P/R>1$. Near the mouth, primary production is limited by depth and turbidity but these large rivers have received organic matter from upstream processing of dead leaves and wood debris. The conditions are heterotrophic again, so $P/R<1$ (Vannote et al., 1980).

Pollution may change dramatically this dynamic equilibrium of the river continuum, and influence, for instance, community composition. This paper describes a model developed to improve understanding of changes in a river community under the effects of pollution by sewage. Solid material settles to the bottom and is decomposed by micro organisms. Their aerobic respiration depletes dissolved oxygen in the water and may cause the mortality of fish. This is a well-known problem, described in textbooks, such as Smith and Smith (1998) and Jørgensen and Bendoricchio (2001).

However, integrated models covering the wide range of aspects of river ecosystems are difficult to build because of partial understanding of these systems and data availability. As noted by Rykiel (1989), ecological modellers have been using one basic knowledge representation scheme, the mathematical equation. This approach severely limits the kind of knowledge that can be represented and how knowledge is organized. Given that much ecological knowledge is incomplete, qualitative and fuzzy, expressed verbally and diagrammatically, ecologists have no effective technology for using it in a meaningful way.

Rykiel (1989) argues that research in artificial intelligence may provide tools in the form of symbolic computing techniques for manipulating qualitative knowledge. These tools may be useful for rapid assessment of assumptions, hypotheses or other ideas in a theoretical context; determining the consequences and logical consistency of long and complicated ecological reasoning pathways. This way, these tools should allow an ecologist to think mostly about the ecological problem and much less about the mechanics of computing.

Qualitative reasoning is an area of artificial intelligence that creates representations of continuous aspects of the world to support reasoning with incomplete knowledge and may provide some of the tools foreseen by Rykiel. Qualitative reasoning may be useful for building conceptual models, that is, models designed to improve understanding on how the components of a system are connected by processes (Jørgensen and Bendoricchio, 2001). Conceptual models aid in devising concepts and proposing hypotheses, so that it is possible to demonstrate the 'consequences of what we believe to be true' (Grimm, 1994).

The approach we take in the work described in this paper has been successfully applied to population and community ecology (cf. Salles and Bredeweg, 2003; Salles et al., 2003). A previous version of the model described here was used for didactic purposes in the *First Workshop on Qualitative Reasoning and Stream Ecosystem Recovery*[1] during which the use of qualitative reasoning techniques for representing aspects of stream ecosystem recovery was discussed with experienced ecologists.

In this paper, we describe the model building process, difficulties found and solutions we have adopted. We also discuss what the participants of the *First Workshop on Qualitative Reasoning and Stream Ecosystem Recovery* thought about using qualitative models to support research, decision-making, education and training in water ecology. In Section 2, we present details about problems caused by sewage pollution. The model building process is discussed in Section 3 and the results are described in Section 4. The use of qualitative models and simulations in water ecosystem recovery, according to the perception of ecologists, is presented in Section 5 and related work on qualitative representation of ecological problems in water systems is commented in Section 6. Finally, in Section 7 we present our concluding remarks.

2. The problem

Water bodies are normally poor in dissolved oxygen, due to its low solubility in water. Oxygen concentrations in the atmosphere, for example, are 30 times higher than concentrations in water bodies (Von Sperling, 1996). Therefore, any environmental change or increased levels of consumption may cause significant changes in the dissolved oxygen concentrations in water bodies. Applying this knowledge, dissolved oxygen has been used to assess pollution and the capacity of water bodies' depuration (for example, cf. Von Sperling, 1996).

Introduction of organic matter in a water body influences, directly or indirectly, the consumption of dissolved oxygen. This is due to the activity of decomposers, organisms involved in stabilization processes of organic matter. These organisms use available dissolved oxygen as input for their *respiration* process, a general cellular mechanism that releases energy. From the ecological point of view, the worst effect of water pollution by organic matter is the reduction in dissolved oxygen concentration. The impact of such pollution affects the whole biological community and may be selective for some fish species, given that their susceptibility to reduced concentrations of dissolved oxygen may be different. For example, under low concentrations of dissolved oxygen fish mortality in some species may increase.

Sources of oxygen in a river are re-aeration (oxygen that enters the water from the atmosphere), transportation from effluents and tributaries and the biological process of photosynthesis. The most important sinks are chemical reactions in water (oxidation of organic matter) and the biological process of respiration (found in all living organisms, including plants, animals, micro organisms and decomposers).

Given those sources and sinks, the balance equation for dissolved oxygen (DO) in a segment of a river with constant volume (Tchobanoglous and Schroeder, 1985; Thomann and

[1] First Workshop on Qualitative Reasoning and Stream Ecosystem Recovery (QRSER), held in Jena, Germany, 6–8 March 2003, organized by the University of Jena. For details visit www.qrser.de.

Mueller, 1987) may be presented as follows:

$$\frac{d(DO)}{dt} = [A - OM_{ox}] + [P - R] + [T_{in} - T_{out}]$$

where A is the inflow of oxygen into the water due to re-aeration, OM_{ox} the consumption rate of oxygen due to organic matter oxidation, P the production rate of oxygen due to photosynthesis, R the consumption rate of oxygen due to respiration, and T_{in} and T_{out} are the transportation rates of dissolved oxygen into and out of the river segment.

Assuming that the components $[A - OM_{ox}]$ and $[T_{in} - T_{out}]$ are constant, changes in dissolved oxygen are due to the biological processes of photosynthesis and respiration. Under these assumptions, pollution by sewage will reinforce respiration and therefore will cause lower levels of dissolved oxygen and higher mortality of fish. Management actions may reduce the negative effects of sewage pollution. The model described here, using only qualitative representations of causal relations involving the effects of photosynthesis and respiration processes, shows how effective and ineffective management actions eventually affect the fish stock.

3. The model building process

3.1. *Process-oriented models*

In order to model the effects of sewage pollution and the influence of management actions, we describe the structure of a river system consisting of plants, fishes, decomposers, nutrients, dissolved oxygen and organic matter. This model should support predictions such as: '*if organic matter in water increases, then the amount of oxygen decreases and the amount of fish also decreases*'.

The model was built following the process-oriented ontology (Forbus, 1984). In this approach, changes in the system are always initiated by processes and their effects may propagate to the whole system via causal dependencies. Two modelling primitives are central in this approach: direct *influences* (*I*+ and *I*−) and *qualitative proportionalities* (*P*+ and *P*−). Both express mathematical functions and causal dependencies (Forbus and de Kleer, 1993). To represent dynamics requires expressing differential equations, where constraints are placed on the derivative of a quantity, rather than on the quantity itself. In the process-oriented approach this is modelled by means of direct influences, which are defined as follows: the relation $I+(Y,X)$ means that $dY/dt = (\ldots + X \ldots)$ and $I-(Y,X)$ means that $dY/dt = (\ldots - X \ldots)$.

Indirect influences are modelled with qualitative proportionalities. For example, the relation $P+(Y,X)$ captures the notion that 'Y is qualitatively proportional to X'. This expression means that there is some function (f) which determines Y, depends at least on X and is increasing monotonic in its dependence on X, such that $Y = f(\ldots X \ldots)$ and $dY/dX > 0$. For example, if X is increasing, then Y will increase as well. The notion of 'inversely qualitatively proportional' is defined in a similar way, $P-(Y,X)$, with the implicit function being decreasing monotonic. For example, if X is increasing, then Y will decrease.

Causality is always expressed in a directed way: both expressions $I+(Y,X)$ and $P+(Y,X)$ means X causes change in Y, and not the contrary. Combined direct influences and proportionalities represent how changes start and propagate throughout the system. For example, the notion that photosynthesis rate (*Photo_rate*) sets the value of the derivative of dissolved oxygen (*Oxygen*) is modelled as *I*+(*Oxygen*, *Photo_rate*). The expression *P*+(*Growth_rate*, *Oxygen*) means that oxygen cause changes on fish population via its growth process. The causal flow is then established: the photosynthesis rate adds a positive value on the derivative of dissolved oxygen, which increases. When *Oxygen* is increasing, it causes the fish *Growth_rate* to increase, which ultimately causes the fish population to increase.

Note that, as with qualitative proportionalities, a single direct influence does not determine how the influenced quantity will change (unless it is the only influence). Its effect must be combined with the effects of other direct influences to define their net effect. This operation is called *influence resolution*. Direct influences combine via addition. If they have the same sign or if we know their relative magnitudes, it is possible to determine how the influenced quantity will change. The situation may be ambiguous if the relative magnitudes are not known (or cannot be defined). If there is no further information, the qualitative reasoning engine tries all the possible outcomes. Such ambiguities increase the number of possible states in qualitative simulations.

Influence resolution involving qualitative proportionalities follows the same procedure. If there is only one qualitative proportionality influencing a quantity, the influenced quantity will change in the same direction (if *P*+) or the opposite direction (if *P*−) of the influencing quantity. Combining two or more proportionalities is more complex, as this is not necessarily done via addition (it may be a product or a trigonometric or an exponential function). The choices, as in unresolved direct influences, are to explore different assumptions about the net result, to add more information about the functions represented by the proportionalities or to leave the system try all the possible outcomes (Forbus and de Kleer, 1993).

In qualitative reasoning models, the value of a quantity is represented by the pair *magnitude* and *derivative* (⟨*magn*, *deriv*⟩) and the qualitative values they may assume are represented in an ordered set called the *quantity space*. This set is restricted to the most qualitatively significant states of the quantity. In the model described here, for example, the magnitude of quantities *Amount_of* fish and *Oxygen* can assume values from the quantity space {*low*, *medium*, *high*}. Although their actual numerical values are different, it is possible to establish *correspondences* between qualitative values of different quantities in order to capture, for example, the notion that a high amount of fish requires a high concentration of oxygen (Forbus, 1984). All the derivatives can assume values from the quantity space {*minus*, *zero*, *plus*}.

For our modelling effort, we use a compositional modelling approach (Falkenhainer and Forbus, 1991). Knowledge is encoded in a set of stand alone and reusable partial models called *model fragments*. The set of model fragments is called the *library* and constitutes the domain knowledge about a certain subject. In general, the library allows for building a set of related models with different levels of complexity. For example, the library created in the work described here suffices for building models about photosynthesis, respiration or a combination of the two processes.

3.2. *Qualitative reasoning tools*

The models are implemented in GARP (Bredeweg, 1992), a qualitative reasoning engine that has been used in different domains, including population and terrestrial community ecology (for example, Salles and Bredeweg, 1997; Salles et al., 2003). The graphical interface HOMER (Jellema, 2000; Bessa Machado and Bredeweg, 2002) was used for the model building activity. The simulations were run in GARP and inspected with the model visualization tool VisiGarp (Bouwer and Bredeweg, 2001).

To run a simulation, GARP takes an *initial scenario* as input, which includes a structural description of the system, statements about the relations between the entities, causal dependencies and the initial values of some quantities. The reasoning engine assembles the model fragments that match the scenario, proceeds to the influence resolution of direct influences and proportionalities and knowledge constraints are taken into account in order to define possible state transitions. This way, from the initial scenario one or more initial states may be produced.

A qualitative *state* is defined as a description of the structure of the system, including the set of (causal) dependencies between quantities and a distinct set of quantity values. Each state is described by a combination of model fragments. The simulation proceeds by means of iterative operations of the reasoning engine, that create new states by doing influence resolution with the active direct influences and proportionalities, computing the values of quantities, selecting new sets of model fragments (if required) and checking new state transitions, until no more transitions can be found.

Note that some conditions that hold in a state may not be true in another state, leading to some model fragments being removed and others being included in each state. This way, qualitative models are able to represent changes in the system structure during a simulation. For example, if a process becomes inactive in a certain state, then the related model fragment is removed in the next state and the direct influence is not longer represented in the system structure. Each unique sequence of states connected by state-transitions is called a *behaviour path* and the diagram with all the states produced in the simulation is called *state graph* or *behaviour graph*. The state graph constitutes all the possible behaviours of the system, according to the initial scenario.

All the elements of the simulation, including entities, dependencies, behaviour paths and the state graph, the quantity values in each state and the model fragments selected in each state can be visualized with VisiGarp. Some examples are given below, in Section 4.

3.3. *Specifications of the model*

A qualitative model includes some entities (or objects), the components of the system of interest. The model described here includes the following entities: ‘river’, viewed as a ‘container’ that contains ‘biological entities’: ‘aquatic plants’,

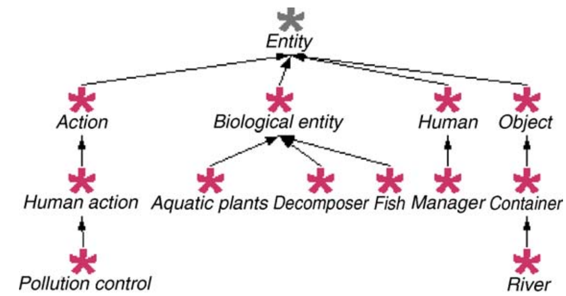

Fig. 1 – Hierarchical representation of the entities involved in the model.

‘decomposer’ and ‘fish’. There is also a (human) ‘manager’, who may perform a task (‘human action’), namely ‘pollution control’ in the river. The entities included in the model are depicted in Fig. 1.

Relevant properties of the entities are represented as *quantities*. For example, some properties of ‘river’ are defined by the concentrations of nutrients, organic material and dissolved oxygen. These properties are represented by the quantities *Nutrient*, *Organic Matter* and *Oxygen*. It is assumed that *Nutrient* and *Organic Matter* always exist, although their values may increase or decrease. This knowledge is captured by assigning their magnitudes a quantity space with a single qualitative value, representing the interval {*plus*}. The quantity space associated to *Oxygen* is {*low*, *normal*, *high*}.

The amount (mass) of aquatic plants, decomposers and fish are represented by means of the quantity *Amount_of*, with quantity space {*low*, *normal*, *high*}. Processes may change the values of these quantities. The amount of decomposers changes due to the process ‘Decomposer growth’, a combination of all the processes that increases the whole mass of the group of decomposers (such as the assimilation of digested organic matter and increase in the number of individuals due to reproduction), and processes that reduce the mass of decomposers (such as excretion, loss of part of their bodies and mortality). The rate of this process is defined as:

Decomposer growth rate = mass input − mass output

Similarly, the mass of fish may change due to the process ‘Fish growth’ at the rate:

Fish growth rate = mass input − mass output

Growth of aquatic plants (which includes both phytoplankton and rooted plants) may be described by the process ‘Plant growth’, seen as the balance of photosynthesis and respiration processes. The rate is defined as:

Net production rate = photosynthesis rate − respiration rate

All the rates (*Decomposer growth rate*, *Fish growth rate* and *Net production rate*) have quantity space {*minus*, *zero*, *plus*}. For example, when *Net production rate* has value *minus*, both the mass of plants and the dissolved oxygen are decreasing.

Actions of management (controlling pollution) are modelled by means of the quantity *Control*. This quantity is a rate, representing a number of processes, such as reduction of discharge and removal of pollutants, taken in order to control pollution. Note that the quantity *Control* does not represent a decision of a particular manager but the balance between management actions and pollution activities. Its value can be calculated as:

$$\text{Control} = \text{actions that control pollution} - \text{actions that increase pollution}$$

Control may assume values contained in the quantity space {*minus*, *zero*, *plus*}. Effective management, in which actions that control pollution are stronger than the actions that increase pollution, is modelled by assigning to *Control* the value *plus*. In this case, the amount of organic matter in the river will decrease. When *Control* = *minus*, positive actions are relaxed and activities that increase pollution are stronger, so that the quantity of organic material in the river will increase. It is therefore an ineffective management practice. When *Control* = *zero*, actions that cause pollution and actions taken to control it are equivalent and the amount of organic material remains stable.

3.4. *The library of model fragments*

The library consists of 11 model fragments. The most general is the model fragment 'River', a view that describes static features of the system. This model fragment presents the three quantities associated to the river (*Organic matter*, *Nutrient* and *Oxygen*). It is assumed that there is a correspondence between the quantity spaces of *Organic matter* and *Nutrient*. The correspondence does not mean that the two quantities have equal numerical values, but that the qualitative values of one quantity correspond to the same qualitative values of the other quantity (Bredeweg, 1992). The model fragment represents the idea that when organic matter is increasing or decreasing, nutrients change in the same direction. This is captured as a qualitative proportionality relating *Organic matter* and *Nutrient*:

P+(Nutrient, Organic Matter)

Three processes are described by means of seven model fragments. The model fragment 'Net effect photosynthesis and respiration' includes the model fragment 'River' and the configuration of the entities defines that the river contains aquatic plants. The *Net production rate* is influenced by the concentration of nutrients and is a direct influence on both the amount of plants and dissolved oxygen. These dependencies are modelled as follows:

P+(Net_production rate, Nutrient)

I+(Amount_of plant, Net_production rate)

I+(Oxygen, Net_production rate)

There is a positive feedback loop from the amount of plants to the rate, showing that when the amount of plants increases, the rate also increases:

P+(Net_production rate, Amount_of plant)

The model fragment 'Simplify net effect' was created to simplify the simulations, reducing ambiguities in the model and therefore the number of possible states. This is obtained by assuming that the derivatives of both quantities *Amount_of plant* and *Net_production rate* are equal. With this information, the qualitative simulator considers only situations in which both quantities are simultaneously increasing, decreasing or stable and avoids other combinations, for example, a decreasing rate with a stable amount of plants.

Central to these models is the notion that when organic matter increases, the *Decomposer growth rate* also increases, and as a consequence dissolved oxygen is reduced. These concepts are captured in the model fragment 'Organic matter oxidation'. Here, *Decomposer growth rate* is a positive direct influence on the amount of decomposers, and a negative direct influence on both *Organic matter* and *Oxygen*. It is assumed also that the growth rate receives a positive indirect influence from the amount of decomposers:

I+(Amount_of decomposer, Decomposer growth rate)

I–(Organic matter, Decomposer growth rate)

I–(Oxygen, Decomposer growth rate)

P+(Decomposer growth rate, Amount_of decomposer)

Similarly, to the simplification implemented in plant net production, the model fragment 'Simplify organic matter oxidation' assumes that the derivatives of both quantities *Amount_of decomposer* and *Decomposer growth rate* are equal.

Net production rate is an important quantity for defining the conditions of water ecosystems. When photosynthesis is greater than respiration, the concentration of dissolved oxygen increases, and when it is smaller than respiration, dissolved oxygen is removed from water. This condition may be fatal for many living organisms, like fishes. In order to characterize an environment in which dissolved oxygen concentration increases, we created the model fragment 'Relations between production and consumption'. It sets the value of *Decomposer growth rate* as being smaller than *Net production rate*. This condition is identified by an assumption labelled: 'Plant greater than decomposer'. The effect of including this assumption in the model fragment is that this fragment only becomes active during the simulation if the assumption is also included in the initial scenario.

Relations between fish population growth and dissolved oxygen concentrations are represented in the model fragment 'Fish oxygen requirement'. The influence of *Oxygen* on *Fish growth rate* is represented by a positive proportionality:

P+(Fish growth rate, Oxygen)

There is a direct influence of *Fish growth rate* on the *Amount_of fish* imposed by a process, and the notion that '*when the amount of fish is increasing, so is the growth rate*' is captured by a proportionality:

I+(Amount_of fish, Fish growth rate)

P+(Fish growth rate, Amount_of fish)

Two other assumptions are represented in the 'Fish oxygen requirement' model fragment: one defines that the amount of *Oxygen* dissolved in water is greater or equal the *Amount_of fish*, and the other establishes a correspondence between the qualitative values *medium* of these two quantities.

An additional model fragment concerning fish growth rate was introduced in the library in order to simplify the simulations. As with the plant and decomposer components, the model fragment 'Simplify fish oxygen requirement' implements the assumption that the derivatives of both quantities *Amount_of fish* and *Fish growth rate* are equal.

Finally, we modelled management actions by using a special kind of model fragment, the *agent model* (Bredeweg, 1992). This model fragment is used to implement complex processes or some external influences. The most general model fragment is called 'Pollution control' and represents a human manager of the river who performs a task, keeping pollution under control. Associated to the entity 'Manager' there is the quantity *Control*, a rate that directly and negatively influences the quantity *Organic matter* in the river:

I–(Organic matter, Control)

This model fragment has two model fragments as subtypes: 'Effective control' and 'Ineffective control'. The former sets the value of quantity *Control* in ⟨*plus*, *zero*⟩. The magnitude *plus* indicates an effective management practice, and derivative *zero* means that this practice is constant. As a result, the amount of organic matter in water will decrease. In model fragment 'Ineffective control' the value of *Control* are set in ⟨*minus*, *zero*⟩, indicating constant ineffective control. The result is that organic matter in water will increase.

4. Simulations and results

In this section, two simulations are described. The first demonstrates that effective control of pollution results in the fish stock increasing. The second simulation describes what happens in the opposite situation, in which activities that increase pollution are stronger than the actions that would reduce it. A comparison between the two simulations illustrates how the use of an assumption, defining that plant growth rate is greater than decomposers growth rate, may reduce the number of ambiguities and therefore the size of the state-graph.

4.1. Simulating an effective management practice

Starting a simulation with the initial scenario in which the quantities *Amount_of* plants, decomposers and fish equal to ⟨*normal*, ?⟩, *Control* equals to ⟨*plus*, *zero*⟩, and the assumption 'Plant greater than decomposer' is included, a decrease in the amount of organic matter in the river is expected. As a consequence, decomposers should decrease and will consume less dissolved oxygen. The quantity *Oxygen* may then increase. Given that it has a positive influence on *Fish growth rate*, fish is likely to increase as well. The full simulation has 17 states, with three initial states ([1, 2, 3]) and two end states, that is, states where the behaviour path stops ([8, 9]). Fig. 2 shows VisiGarp screenshots of the full simulation and diagrams representing the values of the four quantities (the mass of fish, oxygen, plants and decomposers) in the behaviour path through the states [2] → [7] → [9]. Given the constraints included in the model, there is no state in which decomposers become greater than the plants and the fish; also, it does not happen that dissolved oxygen decreases while fish increases.

Fig. 3 shows how causality flows. It represents the causal model in state 9 of the simulation shown above. Boxes represent the quantities, their quantity spaces and their current values. Triangles represent the values of derivatives (the quantity is increasing or decreasing) and black balls represent derivatives equal to zero (the quantity is stable). For example, at the left hand side of the figure 'control1' has value

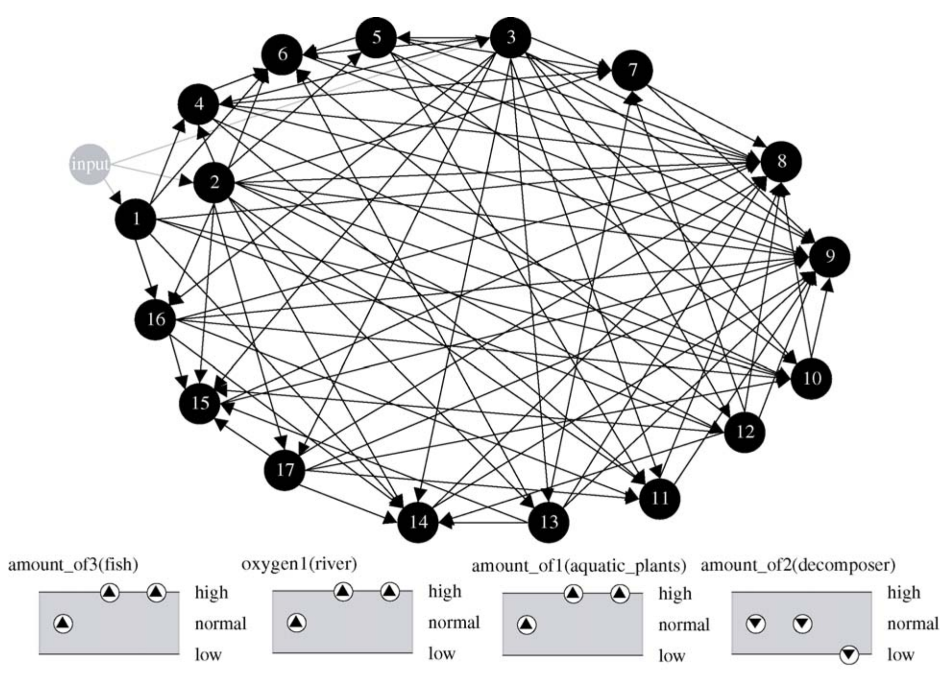

Fig. 2 – State graph of the full simulation of an effective management practice, and diagrams showing the values of four quantities in the behaviour paths [2, 7, 9].

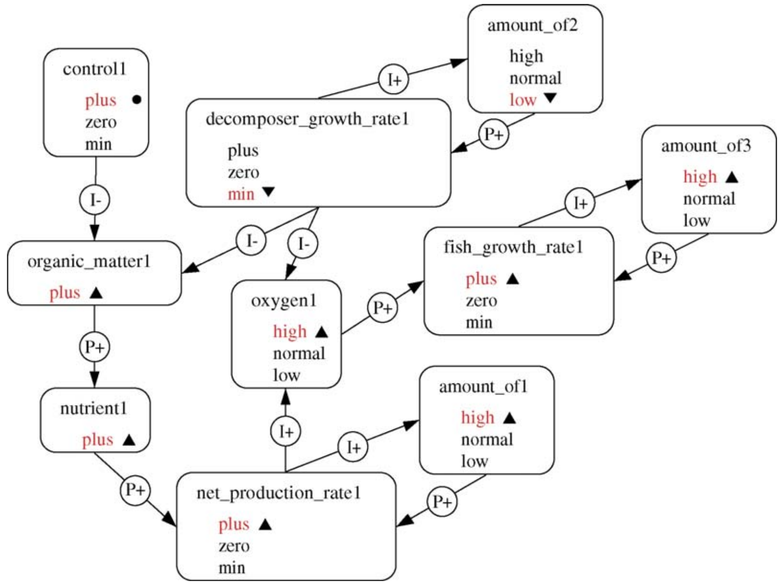

Fig. 3 – Causal dependencies in state 9 simulating effective management. Quantities 'amount_of 1, 2, 3' represent biomass of plant, decomposer and fish components, respectively.

⟨*plus*, *zero*⟩ and starts the change that propagates through the causal chain. Note that, after influence resolution of direct and indirect influences, the quantities 'organic matter1' and 'nutrient1' become stable (derivatives equal to *zero*), while 'oxygen dissolved1' has value *high* and is increasing, the mass of decomposers ('amount_of2') is *low* and is decreasing, and the mass of fishes ('amount_of3') is *high* and is increasing. The causal model presented here supports an explanation for the question: "*Why does effective control of pollution reduce the amount of decomposers and increase the fish stock*"?

4.2. *Simulating an ineffective management practice*

Now imagine a situation in which, for some reason, the result of the management actions turn out to be ineffective. As discussed above, this can be modelled by assigning to *Control* the qualitative value ⟨*minus*, *zero*⟩. Given that in this case we are not assuming that plant growth rate is greater than decomposer growth rate, it is expected that the system will display more complex behaviour and a bigger state graph, giving that there will be more organic matter on the water and less constraints for decomposers to grow. Fig. 4 shows the HOMER screenshot of the initial scenario for simulating ineffective management.

This simulation produces 69 states, with different combinations of values of the 10 quantities included in the model. The states 62–65 are end states of different behaviour paths and each of them represents a situation in which the *Amount of fish* has value *low*, following the quantity *Oxygen* (Fig. 5a).

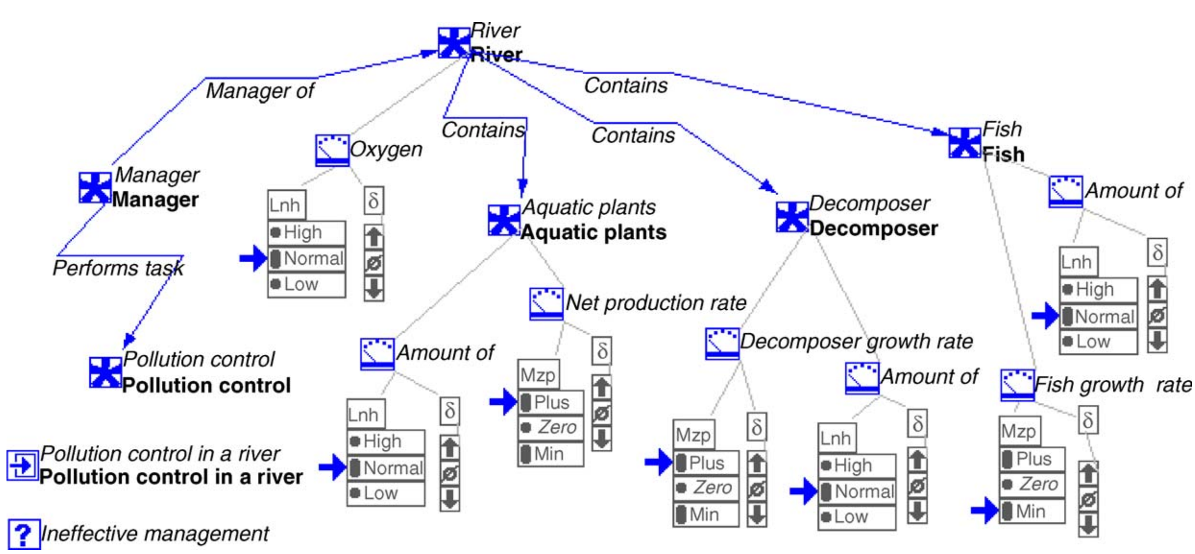

Fig. 4 – Initial scenario for simulating ineffective management. Note that the initial values of some quantities are defined here and that the *Ineffective management* assumption is included.

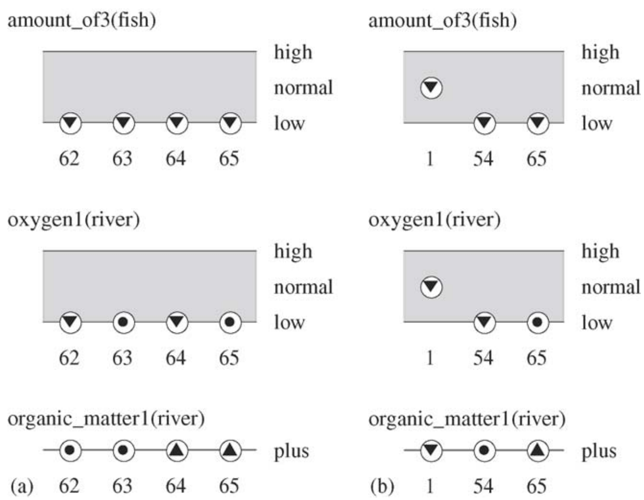

Fig. 5 – Selected states of simulating ineffective management. (a) Final states of the simulation; (b) a selected behaviour path.

A sequence like [1] → [54] → [65] shows the expected behaviour of the quantities *Organic matter*, *Oxygen* and *Amount of fish* (Fig. 5b).

The 69 states created during the simulation predict what is expected from a river being polluted by organic matter without control: organic matter increases, and as a consequence decomposers also increase. Given the causal links between organic matter and nutrients, and between nutrients and net production in plants, an increase in the amount of dissolved oxygen is also expected. However, this situation may change as soon as decomposers start growing. Decomposers put contrary influences on many quantities. They reduce the amount of organic matter, contrary to the positive effect of pollution on this quantity. Simultaneously, decomposers consume dissolved oxygen, contrary to the net production by plants. Influence resolution under these conditions is not an easy task because there are many ambiguities. As no explicit assumptions were introduced in the model, the qualitative simulator GARP tries all the possible combinations.

As a result, the simulation produces states representing all the possible qualitative situations of the system: (a) both *Oxygen* and *Amount of fish* have value *normal*; (b) both *Oxygen* and *Amount of fish* have value *high*; (c) *Oxygen* has value *high* and *Amount of fish* has value *normal*; (d) both *Oxygen* and *Amount of fish* have value *low*. Note that the 'forbidden' combination (the fish component going to *high* while dissolved oxygen goes *low*) was not found in the behaviour graph.

As described above, the two simulations illustrate the effects of management actions on the size of the fish stock. Although it is a well-known problem, the added value of the qualitative model is to make explicit the causal influences that explain the results. This way, the model is a useful tool to show the role of processes as the initial cause of changes, and how the effects of processes propagate to the rest of the system. Finally, being a conceptual model, this model shows the 'consequences of what we believe to be true' (Grimm, 1994) and improves understanding of the structure and behaviour of the system described.

5. The use of qualitative models in water ecology

River ecologists are interested in alternative approaches to ecological modelling because traditional approaches, mostly based on mathematical equations, may be inadequate to implement ideas such as those expressed by the River Continuum Concept. Perhaps the most important aspect is that river ecologists need to develop conceptual models in order to represent their knowledge and to understand the systems they are dealing with. As pointed out by one of the participants of the *First Workshop on Qualitative Reasoning and Stream Ecosystem Recovery*, "conceptual thinking is the only way to understand ecology".

Some features of qualitative reasoning models may enhance research and applications in stream ecosystem recovery. The group in the *Workshop* mentioned as positive points the possibility of creating a rich vocabulary to support communication between researchers and the public, and to build a classification of different types of ecosystems; a compositional modelling approach that allows for reusability of model fragments and for combining 'simpler' models to scale up to more complex problems; explicit representations of causality that can support explanations about the system structure and behaviour.

The participants of the *First Workshop on Qualitative Reasoning and Stream Ecosystem Recovery* believe qualitative models have a role to play in research, decision-making, management and education, and stressed the point that these models may be important for speeding the implementation of new European and Brazilian legislation and directives for water management, that require decentralization (for example, using the river's catchment area as a territorial unity for management actions), participation (that is, the involvement of the whole society in the decision making process) and the integration of multiple uses for achieving the sustainable use of water resources.

6. Qualitative reasoning and water related ecological problems

Qualitative reasoning techniques have been used in hydro-ecological modelling with encouraging results. After initial work representing qualitative knowledge about water resources by Antunes et al. (1987) and Câmara et al. (1987), in which directed sign graphs are used to propagate the influences of human actions, a more comprehensive work was developed by Guerrin (1991). In this work, he describes applications in management of hydro-ecological systems using combinations of linguistic observations, measurements and analytical results by using a qualitative algebra. However, these works do not support representations of the dynamic aspects of the systems, as those described here.

Empirical knowledge gained by freshwater ecologists on the functioning of salmon spawning areas and its impact on mortality in early stages was the basis for a qualitative model built by Guerrin and Dumas (2001a,b). Their model is a qualitative representation of ordinary differential equations, and was implemented in the qualitative simulator QSIM (Kuipers, 1986). The objective of the model is to make predictions about the survival rate of salmon under various scenarios. Their approach also introduces a real time dating and duration in a purely qualitative model. The whole model is decomposed into two parts, each part representing processes that occur at different time-scales (fast and slow). Output shows the behaviour of variables of interest in different situations. For example, mortality rates influenced by oxygenated water and plugging of gravel interstices near the bed surface. This approach captures the dynamics of the system, but causality is not explicitly represented, and as such differs from the GARP models presented in this paper. Also, they do not use the compositional modelling approach to build and assemble model fragments. Therefore, it is more difficult to implement assumptions that may reduce the complexity of the simulations, and to combine models to address more complex problems.

A different approach was taken by Heller and Struss (1996), who describe qualitative models involving spatial distribution of parameters and processes in hydro-ecological systems. These authors have developed a processes-oriented approach to model-based diagnosis, which was applied to problems in water treatment plants (Heller and Struss, 2002). The latter work does not present simulation models, but an implemented system for model-based situation assessment, identification of possible causes of the observed deviations from expected behaviour of the system and therapy proposition. It is, therefore in many ways different from the work we describe here.

A similar approach to ours is taken by Araújo et al. (2004). This work describes different sources of pollution and their effects on the quality of water. Their models create representations for discharges coming from sewage treatment plants, for polluted and non-polluted river segments, for calculations of the deficit of oxygen (in relation to the saturation point) in water, and for process such as re-aeration and transport in the surface of the water.

As demonstrated in this section, qualitative reasoning models are now covering a wider range of water related ecological problems. In an area with serious problems of partial understanding and noisy data, this approach is proving to have a high potential of applications.

7. Discussion and concluding remarks

Modelling the wide array of physical, chemical and biological aspects of stream ecosystems put a number of challenges both for the qualitative reasoning and ecological modelling communities. Some were approached in the exploratory studies described in this paper.

We present a simulation model about a river being polluted by sewage and the consequent increased mortality of the fish component. Two simulations with this model are discussed, showing how effective and ineffective management practices may be used to control fish stocks in the river. Some positive aspects of the approach described here are the use of incomplete knowledge and qualitative data to build models that mimic what is normally done with differential equations, the explicit representation of objects and the use of everyday vocabulary to describe concepts, relations, situations and mechanisms of change and the explicit representation of causality that grounds explanation for why questions about the system's behaviour.

Some limitations of the approach are commented here, mainly with respect to the reusability of previous work and the occurrence of ambiguities due to inaccuracy in the representation of qualitative knowledge. We describe the representation of domain knowledge in partial models (model fragments), that can be reused and combined to build models of different levels of complexity and to describe different states the system goes through during a simulation. This approach gives more flexibility to the modelling process and allows for addressing more complex water related problems. However, no previous work could be reused to produce a more complex representation of water pollution, restricting our work to relatively simple model of a well-known problem.

Due to the use of incomplete knowledge, ambiguities are likely to appear in qualitative models and may increase the number of states produced in a simulation. We show that assumptions can be implemented as correspondences and inequalities between quantities, so that ambiguities can be reduced. However, it is necessary to better explore domain knowledge in order to create representations for realistic assumptions and play with them to obtain alternative perspectives of the systems of interest.

This exploratory study indicates some challenges for the development of qualitative theories of water ecosystems. Compared to the qualitative theory of population dynamics also implemented in GARP (see Salles and Bredeweg, 1997; Salles et al., 2003) there are some points worth to mention in this discussion.

Water ecosystems result of strong interactions between biological, physical and chemical phenomena. In our model, for instance, dissolved oxygen is a limiting factor for biological communities. The result is a complex network of influences that simultaneously affect the energy flow and cycling of nutrients. In fact, we modelled the influences from processes net production of plants and respiration of decomposers both on dissolved oxygen and on the amount (mass) of plants and decomposers. Dissolved oxygen is related to energy storage (in photosynthesis) and release (in respiration), while mass is related to producing organic material (in photosynthesis) and with consumption of that material (in respiration).

It seems that the way ecologists usually think about processes photosynthesis and respiration carries a mixture of concepts involving matter and energy. These processes are complex and qualitative theories involving these two processes may require the development of specific ontologies. We argue that a robust qualitative theory of water ecosystems representing energy flow, nutrient cycling and aquatic population and community dynamics will use three ontologies, the *number_of* ontology already implemented (Salles and Bredeweg, 1997) and those we called *energy_of* and *amount_of*.

Ongoing work includes the development of the *energy_of* and *amount_of* ontologies, implementation of basic processes of photosynthesis and respiration and more complex representations of water ecological systems. We believe that the use of qualitative reasoning models in stream ecosystem recovery and other water-related ecological phenomena have the potential to overcome some of the problems raised by Rykiel (1989) and to become a major breakthrough in conceptual modelling for research, management, training and education.

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REFERENCES

Antunes, M.P., Seixas, M.J., Câmara, A.S., Pinheiro, M., 1987. A new method for qualitative simulation of water resource systems. 2. Applications. Water Resour. Res. 23, 2019–2022.

Araújo, S.C.S., Salles, P., Saito, C.H., 2004 Modelos Qualitativos, Baseados na Dinâmica do Oxigênio Dissolvido, para Qualidade da Água em Bacia Hidrográfica. In: Saito, C.H., (Ed.), Desenvolvimento Tecnológico e Metodológico para Mediação entre Usuários e Comitês de Bacia Hidrográfica. Brasília, Departamento de Ecologia da Universidade de Brasília, pp. 9–24.

Bessa Machado, V., Bredeweg, B., 2002. Investigating the model building process with HOMER. In: Bredeweg, B. (Ed.), Proceedings of the International workshop on Model-based Systems and Qualitative Reasoning for Intelligent Tutoring Systems. San Sebastian, Spain, June 2, pp. 1–13.

Bouwer, A., Bredeweg, B., 2001. VisiGarp: graphical representation of qualitative simulation models. In: Moore, J.D., Luckhardt Redfield, G., Johnson, J.L. (Eds.), Artificial Intelligence in Education: AI-ED in the Wired and Wireless Future. IOS-Press/Ohmsha, Osaka, Japan, pp. 294–305.

Bredeweg, B., 1992. Expertise in Qualitative Prediction of Behaviour. Ph.D. Thesis. University of Amsterdam, Amsterdam, The Netherlands.

Câmara, A.S., Pinheiro, M., Antunes, M.P., Seixas, M.J., 1987. A new method for qualitative simulation of water resource systems. 1. Theory. Water Resour. Res. 23, 2015–2018.

Falkenhainer, B., Forbus, K., 1991. Compositional modeling: finding the right model for the job. Artif. Intell. 51 (1–3), 95–143.

Forbus, K.D., 1984. Qualitative process theory. Artif. Intell. 24, 85–168.

Forbus, K., de Kleer, J., 1993. Building Problem Solvers. MIT Press, Cambridge, MA.

Grimm, V., 1994. Mathematical models and understanding in ecology. Ecol. Modell. 75/76, 641–651.

Guerrin, F., 1991. Qualitative reasoning about an ecological process: interpretation in hydroecology. Ecol. Modell. 59, 165–201.

Guerrin, F., Dumas, J., 2001a. Knowledge representation and qualitative simulation of salmon reed functioning. Part I: qualitative modelling and simulation. BioSystems 59, 75–84.

Guerrin, F., Dumas, J., 2001b. Knowledge representation and qualitative simulation of salmon reed functioning. Part II: qualitative model of reeds. BioSystems 59, 85–108.

Heller, U., Struss, P., 1996. Transformation of qualitative dynamic models—application in hydro-ecology. In: Iwasaki, Y., Farquhar, A., (eds.), Proceedings of 10th International Workshop on Qualitative Reasoning (QR'96). AAAI Technical Report WS-96-01.

Heller, U., Struss, P., 2002. Consistency-based problem solving for environmental decision support. Comput.-Aided Civil Infrastructure Eng. 17, 89–92.

Jellema, J., 2000. Ontwerpen voor ondersteuning—De rol van taakkennis bij ondersteuningsontwerp. Master thesis. University of Amsterdam, Amsterdam (in Dutch).

Jørgensen, S.E., Bendoricchio, G., 2001. Fundamentals of Ecological Modelling, third ed. Elsevier Science, Oxford.

Kuipers, B., 1986. Qualitative simulation. Artif. Intell. 29, 289–338.

Rykiel, E.J., 1989. Artificial intelligence and expert systems in ecology and natural resource management. Ecol. Modell. 46, 3–8.

Salles, P., Bredeweg, B., 1997. Building qualitative models in ecology. In: Ironi, L. (Ed.), Proceedings of the 11th International Workshop on Qualitative Reasoning (QR'97). Instituto di Analisi Numerica C.N.R., Pubblicazioni no. 1036, Pavia, Italy, pp. 155–164.

Salles, P., Bredeweg, B., 2003. Qualitative reasoning about population and community ecology. AI Mag., winter 24 (4), 77–90.

Salles, P., Bredeweg, B., Araújo, S., Neto, W., 2003. Qualitative models of interactions between two populations. AI Commun. 16 (4), 291–308.

Smith, R.L., Smith, T.M., 1998. Elements of Ecology, fourth ed. Addison Wesley Longman, San Francisco, CA.

Tchobanoglous, G., Schroeder, E.D., 1985. Water Quality—Characteristics, Modelling, Modification. Addison-Wesley Publ. Co, EUA.

Thomann, V.R., Mueller, 1987. Principles of surface Water Quality Modeling and Control. Harper & Row Publishers, EUA.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The River Continuum Concept. Can. J. Fish Aquat. Sci. 37, 130–137.

Von Sperling, M., 1996. Introdução à qualidade das águas e ao tratamento de esgotos, second ed. Belo Horizonte. Departamento de Engenharia Sanitária e Ambiental. Universidade Federal de Minas Gerais.