A qualitative model of the nutrient spiraling in lotic ecosystems to support decision makers for river management

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Abstract

The spiraling of resources in stream ecosystems is a well known phenomenon in the scientific literature. We implemented the necessary components of a nutrient cycle in a qualitative reasoning approach. The model includes entities that represent segments of a river and quantities for nutrients, autotrophs, and detritus, and employs three rates: uptake rate (from nutrients to autotrophs), retention rate (from autotrophs to detritus), and release rate (from detritus to nutrients) within the nutrient cycle. Each river segment also has a flow rate allowing only the nutrients to move from one segment to another. To enable the users to specify the character of a river segment we used *attributes* and to represent influences from the catchment area we used *agents*. The ideas presented in this paper represent our first approach to create an easy-to-use simulation setup so that stakeholders and decision makers can simulate specific scenarios and develop causal models of specific stream phenomena.

Introduction

Many stream ecosystems have suffered decades of degradation. Impacts have included non-point source pollution by, e.g., agricultural runoff, untreated wastewater and erosion, and point sources, such as industrial contamination, municipal wastewater, and urban runoff. Constructions of weirs and dams, channelization, and dredging have reduced the complexity of stream channels. Due to increased recognition of the importance of stream ecosystems for biodiversity and sustainable development, there has been stronger focus on reducing negative human impacts. This may occur through wastewater treatment, reduction of industrial inputs, restoration of the stream channel, improved agricultural practices, and other land-use changes in riparian areas. The goal of these activities is to improve conditions in the stream and thus aid recovery of the ecosystem.

Although there are many possible ways to facilitate stream ecosystem recovery the effects of any particular management action are difficult to predict. Yet decision makers need predictions in order to plan their activities. Quantitative ecosystem models may provide such predictions, but they are not only difficult to parameterize, but also difficult to explain to non-experts. Stream ecosystems are especially problematic to model because of our generally poor understanding of ecosystem interactions in the recovery and regeneration process. Nevertheless, scientists and resource managers have extensive expert knowledge and qualitative data, based on years of ecological research and experience. Such knowledge can be formalized into qualitative models.

The aim is to create an easy to use simulation setup so that stakeholders and decision makers can easily build their own causal models of a specific stream using specific scenarios (see also Salles et al., 2003). We want to formalize as much knowledge as possible, providing the user with ready-to-use model fragments. Here we describe our first approach based on the nutrient spiraling concept with focus on the amount of dissolved nutrients in a chain of stream segments. We present the software tool and the concept used, the implementation of the model, and some scenarios and simulation runs.

Materials and Methods

Qualitative Reasoning

Qualitative Reasoning (QR) is an innovative technique, originating from Artificial Intelligence (AI), that involves non-numerical description of systems and their behaviour, preserving all the important behavioural properties and distinctions. QR models capture the fundamental aspects of a system or mechanism, while suppressing much of the irrelevant detail. Methods such as abstraction and approximation are often used to construct models based on qualitative rather than numerical aspects of a system. This approach makes expert knowledge available to non-experts for direct use in applied contexts. It will help reconcile the conflicting interests of water users and facilitate forecasting, management, and restoration of running waters.

Simulation Software Used

We constructed the models with three software components. The HOMER qualitative model-building environment (Bessa Machado & Bredeweg, 2002) is a graphical tool with which qualitative model fragments can be defined. These are then simulated by the GARP qualitative reasoning engine (Bredeweg, 1992). Finally, the simulation results are inspected with VisiGARP (Bouwer & Bredeweg, 2001).

The Spiraling Concept

The spiraling of resources in an ecosystem is a well known phenomenon in the scientific literature and is neither new nor restricted to streams (Allan, 1995). The downward movement of nutrients was first mentioned in an essay by (Leopold, 1941), who called it rolling motion. The term spiraling was introduced by (Webster & Patten, 1979) to describe the combination of cycling and downhill transport. Associated with each passage through a cycle is a finite downhill displacement that stretches the cycle into a continuous spiral (Elwood, Newbold, O´Neill, & Winkle Van, 1983). The difference between cycling and spiraling is the downstream movement. The spiraling concept is applied to nutrients and to organic carbon dynamics (Newbold, Mulholland, Elwood, & O'Neill, 1982) and has been demonstrated by radiotracer experiments (Ball & Hooper, 1963).

In this study we simplified the nutrient spiraling concept by considering only those components that are strictly necessary (see Figure 1). The amount of autotrophs and detritus is strongly limited by the characteristic of the river segment, while the amount of nutrients is actually calculated by the simulation model. To further simplify, we assume that only nutrients are moving downstream and that the other two components (autotrophs and detritus) of the cycle do not move. The amount of dissolved nutrients moving downstream depends on the flow rate within a river segment.

Results

Implementation

We implemented only the necessary components of a nutrient cycle. The simulation model includes entities that represent objects such as a segment of a river and the sea as the drain of a river. To simplify for the user the process of constructing a scenario, all other properties of a river segment were represented as quantities. We implemented nutrients, autotrophs, and detritus, ignoring aufwuchs, consumers, shredders, and other conceivable properties in the nutrient cycle. Consequently we implemented three rates within the nutrient cycle, namely *uptake rate* (from nutrients to autotrophs), *retention rate* (from autotrophs to detritus), and *release rate* (from detritus to nutrients). The amount (mass) of nutrients, autotrophs, and detritus was implemented with the quantity space QS= {zero, low, medium, high}. The rates were implemented with QS= {zero, plus}.

Each river segment has a flow rate with QS= {zero, low medium, high} as a fourth process. Only the dissolved nutrients can flow into the next downstream river segment. The spatial dynamic of the nutrient spiraling is therefore represented by a chain of river segments, without defining the actual length of each segment. This is a severe simplification, but actually represents the routine of stream water quality assessment quite well, where measurements at sampling points always represent the upstream river segment up to the next sample point regardless of the distance between points.

In our simulation model the only influence an upstream segment has on a downstream segment is the transport of nutrients in the current. The flow rate reduces nutrients in the upstream segment and increases them by the same amount in the downstream segment.

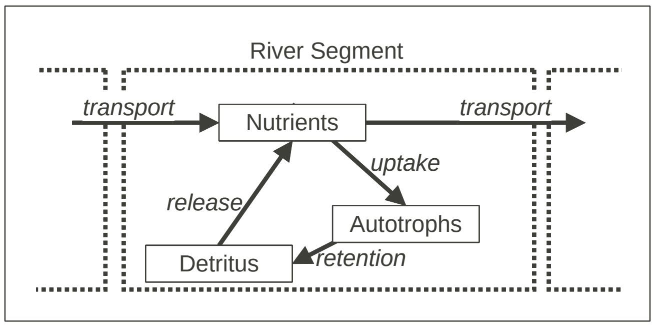

Figure 1: The implemented components of the nutrient spiraling concept, with nutrients as the only component moving downstream (*spiraling*).

Attributes

Our aim is to create a simulation tool that allows users without modelling background to create easily a scenario representing a specific river. Consequently, we used *attributes*[1] to manipulate the properties inside the entity representing a river segment. The user need only label a river segment, e.g., as *canalized* or as *natural* (see Figure 2), and the consequences for the modelling are automatically included by the associated model fragments. Attributes in HOMER are widely applicable and are intuitively understood by the user. At this stage the implemented

[1] In GARP (Bredeweg, 1992) attributes represent non-changing features (as opposed to quantities, which represent changing features). In the work presented in this paper, attributes are used as additional conditions to trigger (or not trigger) certain model-fragments.

attributes (A) for the degradation of a river segment allow specification as A= {canalized, natural, unknown}, for the flow rate A= {zero, slow, medium, high}, and for the sun reaching the river segment A= {no sun, a lot of sun}. The attributes function as conditions in the Model Fragments and consequently define the values of some state variables (see Table 1).

Agents

All objects influencing a river segment from the catchment area were implemented as *agents*. In GARP agents represent exogenous impacts on the behaviour of a system. Again, this was done to simplify the scenario construction process for the users. Agents are a powerful tool in HOMER and the user finds it intuitive to represent, e.g., a *waste water plant* as an agent. At this stage we implemented the agents *spring* as resource of a river, *waste water plant* as source of nutrients, and *forest* as source of detritus. As with the attributes, the agents are used as conditions inside the Model Fragments and consequently cause a manipulation of state variables.

Processes

We adopted the process-oriented ontology (Forbus, 1984) to implement the nutrient spiraling concept into a QR simulation model. This means that changes in the system are always initiated by processes and their effects may propagate to the whole system via causal dependencies. We used *direct influences* (I+ and I-) and *qualitative proportionalities* (P+ and P-) as model primitives to represent mathematical functions and causal dependencies.

Direct influences are used to calculate the derivative of a state variable from the rate of a process. Figure 7 shows all dependencies from the scenario in Figure 4 generated by the simulator. For example, the uptake rate of the nutrients sets the value for the derivative of autotrophs I+ (autotrophs, uptake rate) and for the derivative nutrients I-(nutrients, uptake rate). On the other hand, qualitative proportionalities represent indirect influences on quantities other than state variables, such as monotonic functions. For example, when the amount of autotrophs increases, the uptake rate also increases, and when autotrophs decrease, so does the uptake rate P+ (uptake rate, autotrophs).

The uptake rate has a direct influence to reduce the dissolved nutrients and to increase the amount of autotrophs. The rate is indirectly influenced by the sunshine, the amount of nutrients and autotrophs and a slower flow rate. The retention rate reduces the amount of autotrophs and increases the amount of detritus. It is positively influenced by the amount of autotrophs. The release rate reduces detritus and increases dissolved nutrients by direct influences. It has a positive qualitative proportionality with detritus and a negative one with the flow rate (see Figure 7).

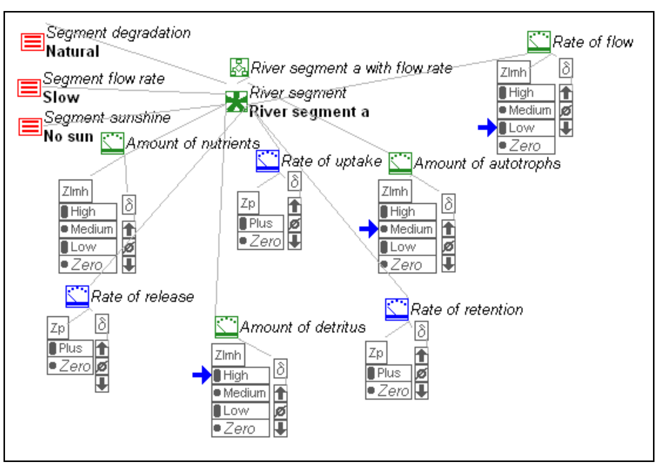

Figure 2: The Model Fragment for a natural, slow flowing river segment which is not reached by much sunlight contains the consequences for the flow rate and the amount of autotrophs and detritus. The value is set by the arrows.

Library of Model Fragments

The model comprises a hierarchical library of model fragments. The most general one is the static MF *River segment*. It implements the three state variables nutrients, autotrophs, and detritus inside the entity river segment. It is followed by the MF *River segments with rates*, which also implements the rates for uptake, retention and release and the flow rate of the river segment. A first block of MFs implements the consequences from the attributes used by the user. For each combination of attributes a MF defines the associated values.

Table 1: The attributes as condition in the 12 MFs (for degradation C: canalized, N: natural; for flow rate H: high, M: medium, L: low; and for sunshine S: a lot of sun, N: no sun) and as consequence the associated values (z: zero, l: low: m: medium, h: high) for the state variables representing the amount of autotrophs and detritus.

Attributes			Autotrophs	Detritus
C	H	S	z	z
C	H	N	z	z
C	M	S	l	l
C	M	N	z	l
C	L	S	m	m
C	L	N	l	m
N	H	S	m	l
N	H	N	l	l
N	M	S	m	m
N	M	N	l	m
N	L	S	h	h
N	L	N	m	h

In Figure 2 we present the MF for a natural, slow flowing river segment which is not reached by much sunlight. The displayed attributes are conditions, which means that they must be selected in the scenario in order for this MF to apply. Note that as a consequence the value for flow rate is set to low, the value for autotrophs is set to medium, and the value for detritus is set to high, as indicated in Figure 2 by arrows. The same MF can be found in Table 1 in the very last row.

At this stage we used this strong limitation to focus on the changes in the amount of nutrients. Our attention is on the nutrient spiraling along a chain of river segments and not within one single segment. Table 1 shows all combinations of the currently implemented attributes and their associated values for the state variables amount of autotrophs and amount of detritus. To achieve a manageable approach at this stage, the situation has been greatly simplified. Note that the amount of nutrients is never fixed and consequently is not limited in its variation.

The next block of MFs is divided into static and process fragments. These 8 MFs describe the rates for the turnover within the nutrient cycle. We used static MFs to turn rates off by setting their value to zero; e.g., release rate is zero when amount of detritus is zero. We used 3 process MFs to turn rates on and to calculate values for the direct influences and qualitative proportionalities described above.

To reduce the ambiguity of the nutrient cycle we introduced a block of 8 MFs which capture all the different qualitative types of the cycle. The MFs *Fast Cycle* and *No Cycle*, e.g., capture the case that all turnover rates are equal (either plus or zero). Consequently we assume that the

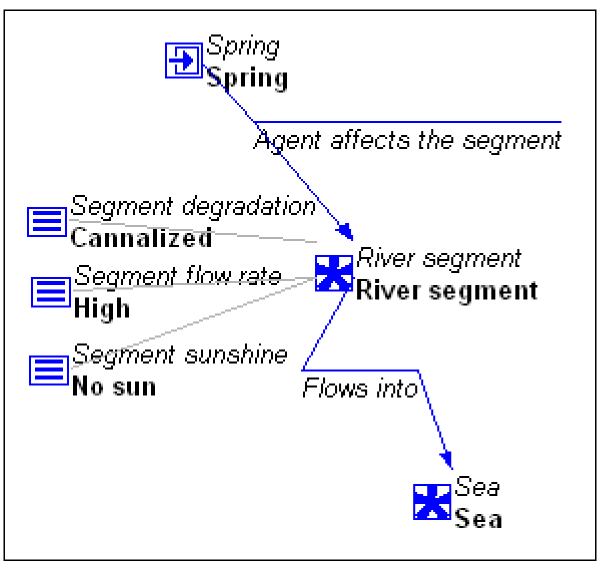

Figure 3: The simplest scenario for a river in our simulation tool composed of a spring, a river segment, and the sea. The river segment here is specified as canalized, high flow rate and no sunshine reaching the river.

amounts of nutrients, autotrophs, and detritus do not change. The other 6 MFs capture the cases that two rates are plus and one is zero or that one rate is plus and two are zero. This causes an increase of one component of the cycle and at the same time a decrease of another component.

One process MF introduces a river segment flowing into the sea, so that the nutrients also flow into the sea. Another MF represents an upstream river segment flowing into a downstream river segment, causing the nutrients to flow downstream at the flow rate of the upstream river segment. As agent model fragments we implemented the influence of a spring flowing into a river segment, a waste water plant polluting a river segment, and forest litter falling into a river segment. The influence of an agent is weighted relative to the flow rate of the river segment. This means, e.g., that a spring has a stronger influence if the flow rate is small then when the flow rate is larger. The same is true for the influence of a waste water plant.

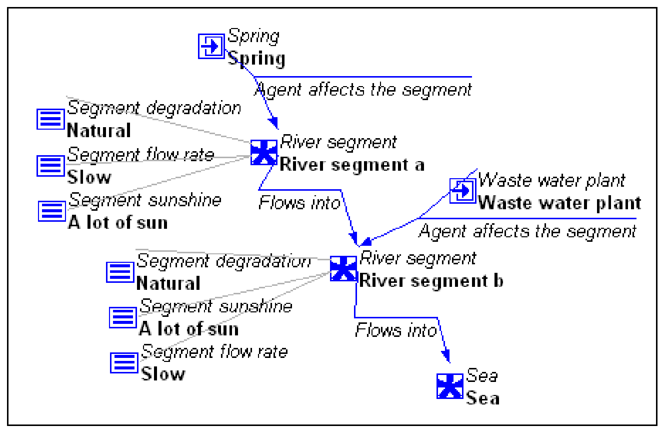

Figure 4: A scenario for a natural stream with slow flow rate and with sunshine. The second river segment is affected by a waste water plant.

Scenarios

The aim of this modelling approach is to reduce the effort needed for a user to construct a scenario for a specific stream. With our approach, in the scenario window of HOMER the user needs only to select entities, attributes that specify the entities, and agents that influence the entities. There is no need to specify any state variable as objective of an entity. The simplest scenario for a river is shown in Figure 3. It represents a spring (agent) flowing into a river segment (entity) which flows into the sea (entity). The attributes used in Figure 3 specify a canalized stream with high flow rate and nearly no sun reaching the river. The stream is composed of two river segments.

The user may create more complex scenarios, using several river segments to represent several sections of a specific stream, e.g. between existing sample points. Each river segment can be characterized by the attributes available. Additionally, agents may be selected that affect the stream. The user can than use the simulation tool to investigate how the nutrient cycle and the amount of nutrients in a river segment change when the character of a river segment is changed in the scenario.

The user may add agents affecting the stream and simulate a scenario with or without the effect of an agent such as a waste water plant. Figure 4 shows as example a stream composed of a spring, two river segments and the sea. Both river segments have the same characteristic but the second segment is influenced by a waste water plant.

Simulations

In this paper we present a selection of simulation runs, starting with simple scenarios. Simulations always start with the value *low* for amount of nutrients in each river segment. Consequently the amount of nutrients will change only if nutrients are added to a river segment. In the scenario shown in Figure 3 only the initial state with low nutrients is calculated by the simulator. The same is true for a river segment with sunshine or for a river segment influenced by a waste water plant. The reason is that because of the high flow rate the influence of the waste water plant is too small. In all cases the activation of the model fragment *No cycle* indicates that no nutrient cycling is calculated.

The result changes if we reduce the flow rate to slow. The scenario with sunshine calculates three states, allowing the

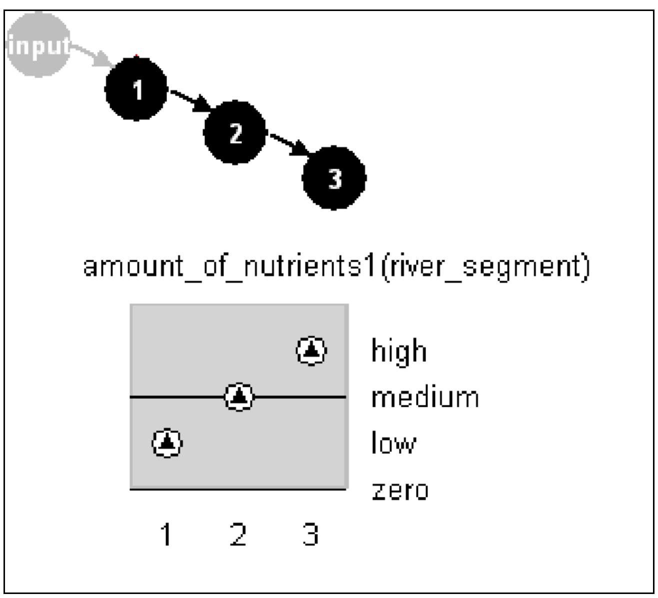

Figure 5: The state graph (top) and value history for the variable amount of nutrients (bottom) for the scenario with one river segment representing a canalized, slow flowing stream with no sunshine and a waste water plant affecting the river segment.

nutrients to fall to zero because of uptake by the autotrophs. Without sunshine nine states are calculated, including an increase of the nutrients to high because of the release rate. The scenario with the influence of a waste water plant is shown in Figure 5 and, starting from one initial state, calculates a total of three states with nutrients *high* in the final state. The reason is that the influence of the waste water plant is large because of the slow flow rate.

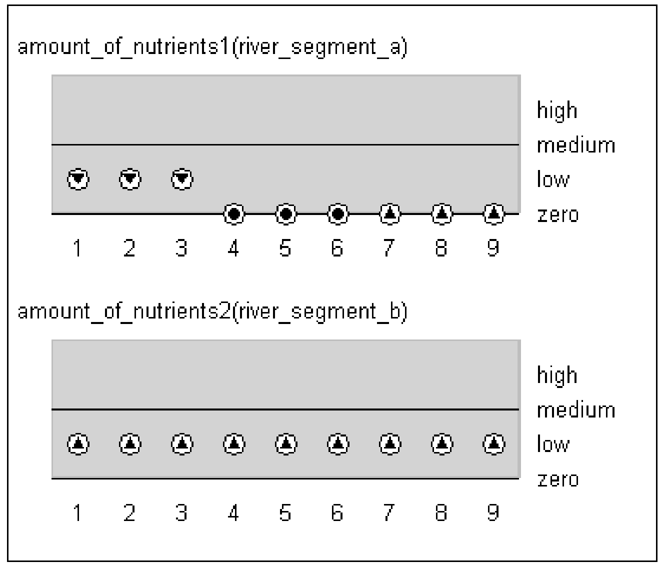

Figure 6: The value history for the variable amount of nutrients in the upstream and the downstream river segment in the scenario shown in Figure 2.

In scenarios with natural river segments we find the MF *fast cycle* to be active more often. Also the uptake rate was active more often, so that the amount of nutrients was reduced to zero. The scenario shown in Figure 4 with two river segments calculates nine states. Figure 6 shows the value history of that simulation. The downstream river segment is influenced by the waste water plant and the downstream flow of the nutrients, causing the value to be constantly low. The upstream segment loses nutrients because of downstream export and the uptake rate.

Additional details to aid understanding of the generated simulation model are presented in Figure 7, which shows all the active dependencies. One can see how the nutrient cycle is implemented with *direct influences* (I+/-) and with *qualitative proportionalities* (P+/-) described above in Processes. It also becomes clear how the flow rate influences the amount of nutrients. In this scenario a spring increases the flow rate of the river_segment_a and a waste water plant increases the amount of nutrients in river_segment_b. The relative degree of influence is determined by the flow rate in the segment.

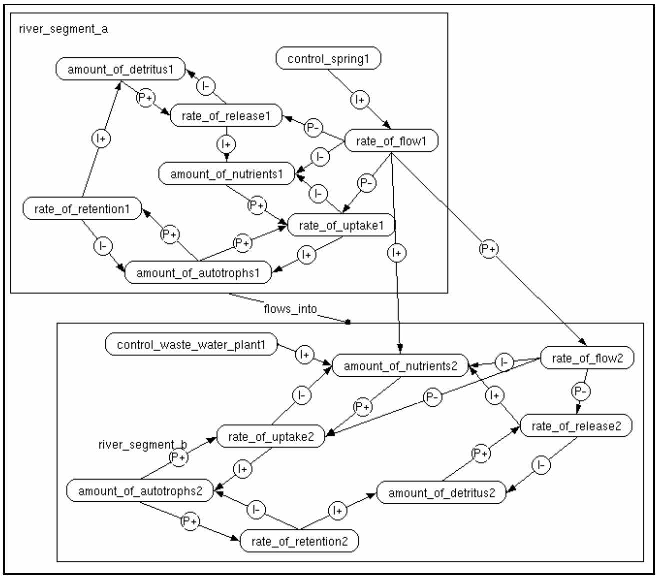

Figure 7: The dependencies of the scenario shown in Figure 4

Discussion

We present an easy-to-us tool for users with no QR background. Constructing a scenario to simulate a specific river system is easy because of ready-made attributes for river segments and agents in the catchment. The Disadvantage is that scenarios with increasing number of river segments will cause more states to be calculated. This makes it difficult for the user to extract the required results and thus to arrive at appropriate decisions. A scenario with three river segments calculates 73 states, and one with 4 segments already has 163 states. To obtain a practical tool for users we need to further reduce ambiguity in the simulation results. This should be done by including more expert knowledge about the nutrient cycle of rivers.

At the same time we must increase the options and features of the simulation tool. More objects in the catchment areas influencing the river are to be implemented as agents. The same is true for the characterization of river segments. This will be possible only if we increase the expert knowledge captured in model fragments.

A disadvantage of our approach is that the user cannot easily implement new features. Implementing a new agent or a new attribute requires knowledge about QR model building and a good understanding of the problem. Consequently our simulation tool has to be adapted to the user needs. This simulation tool has not yet been presented to users, and no complex systems have been modelled. We plan a close collaboration within an EU-funded research project (www.naturnet.org), in order to educate decision makers and stakeholders in the future. This will enable us to develop a tool so users can learn by building a simplified model of their specific problem. In so doing, they can develop an understanding of how the system will behave under specific conditions.

Overall, we have presented a practical concept for a qualitative reasoning simulation tool to calculate the nutrient spiraling in rivers. Our model identifies a fast cycle, no cycle or an incomplete cycle causing an increase of one component and a decrease of another component. We implemented the main influence factors such as sunshine reaching the stream, flow rate, and degradation of the stream. This enables us to interpret structural and functional aspects of stream ecosystems in terms of productivity and stability.

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