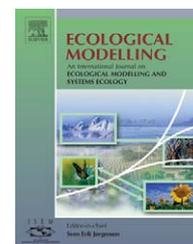


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# A qualitative model for analyzing the effects of anthropogenic activities in the watershed on benthic macroinvertebrate communities

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## ABSTRACT

This paper presents a qualitative reasoning (QR) simulation model for analyzing the effects of watershed development and riparian deforestation on benthic macroinvertebrates. A study of 54 stream sites in the Piedmont of North Carolina, USA provided the knowledge foundation for the model development. A conceptualization of the anthropogenic activities and effects was established and then transferred into a qualitative reasoning (QR) model. Using the compositional approach, watershed–stream corridor interactions were defined by a total of eight reusable model fragments. These partial behavior models were used to progress changes in watershed and riparian condition on the benthic community within the qualitative model. Simulation results of the two activities in the watershed led to tolerant benthic communities. However, watershed development primarily affected communities through degradation in habitat quality while riparian deforestation affected both habitat quality and trophic condition. Further, a significant increase in the number of states generated by the riparian deforestation scenario indicated a greater ambiguity in this system definition and, as a result of the interactions with both habitat quality and trophic condition, reflected increased complexity. The implications of QR models such as this for the field of aquatic ecology include (1) the explicit definitions of watershed and stream corridor interactions; (2) the identification of knowledge gaps, such as the relative importance of habitat and trophic features on the benthos, for directing future ecological research; (3) the identification of potential restoration and management thresholds for guiding ecosystem evolution.

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## 1. Introduction

Conversion of natural landscapes to urban and agricultural uses affects stream ecosystems and the organization of benthic communities in several ways. For this study, we focused on two effects at two different scales: (1) urbanization of forested watersheds on a broader scale and (2) deforestation of riparian systems at the stream-reach scale. With urbanization,

forested watersheds are converted to more impervious surfaces to accommodate growing residential, commercial, and industrial needs. A consequential increase in the volume and intensity of runoff events occurs due to reduced infiltration within the watershed. In addition to an increase in discharge released into the streams, these runoff events often carry higher sediment and nutrient loads and increase habitat scour through streambank erosion. Deforestation of riparian sys-

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tems leads to a reduced supply of Large Woody Debris (LWD) and detrital matter to the stream ecosystem, thereby causing a decline in the retention of sediment and nutrients. The removal of riparian vegetation and protective root materials also increases the risk of streambank erosion and raises water temperatures due to reduced shading. Such ecological services of riparian systems are essential to maintaining high quality habitats and nutrient processing in stream ecosystems. Despite the substantial benefits of a healthy riparian ecosystem, restrictions on activities with adverse impacts remain limited in many areas of the USA (Lee et al., 2004).

With already 45% of streams in the USA designated as either threatened or impaired (USEPA, 2000), the need to unify existing knowledge on the cause and effects of stream ecosystem degradation and enhancement is critical. There are two primary reasons that such a unification of ecological knowledge is particularly challenging: scale and complexity. While aquatic ecosystem interactions are indeed well-researched, the fragmentation and inconsistencies between narrowly focused, small-scale studies make evaluating global implications a complicated task. The scale of ecosystem studies is important because (1) much of the difficulty in defining aquatic ecosystems is due to the inherently high variability of natural systems at very fine scales and (2) it is rarely possible to measure and interpret all relevant ecosystem variables in larger scale, unconfined experiments.

The complexity and interdependent nature of stream ecosystem components make pattern detection and replication exceptionally difficult. Finding the right expression of ecological knowledge for appropriately modeling (and thus simplifying) the complexity of stream ecosystems is challenging. Even the most complex mathematical and numerical models may be unsuccessful in describing the actual mechanisms that create cause-and-effect relationships (Salles and Bredeweg, 2003). In addition, simulations of common deterministic mathematical models provide only a single solution, which is particularly limiting for simulating the succession or recovery of ecosystems over larger temporal and spatial scales.

As Montgomery (2001) has noted, modeling and management of “aquatic ecosystems requires an intimidatingly sophisticated level of knowledge of the spatial context and causal linkages among human actions, watershed processes, channel conditions, and ecosystem response”. A framework that explicitly and comprehensively summarizes the relationships characterizing stream ecosystem form, function, and dynamics, and also addresses the issues of scale and complexity would be beneficial to educators, regulators, researchers, and practitioners engaged in stream ecosystem enhancement.

As with any analysis of ecological systems, acceptable development of such a framework relies on a definition of both structure and function (Karr and Chu, 1999) with which to simplify system complexity into meaningful and relevant processes as well as separate it into its individual parts. By defining processes and parts within qualitative reasoning (QR) models, it is possible to delineate a system’s structure, explicitly represent causality within a system, and predict potential system behavior in response to changes induced in the system. QR offers a technique for building and simulating models by aggregating, articulating, and applying a unique aspect of ecological knowledge, i.e., well-accepted but inade-

quately synthesized ecological interactions. Addressing both issues of scale and complexity, QR can extend current ecological understanding through production of broader, holistic system definitions and predictions. By modeling ecosystem interactions at broader resolutions with QR, small-scale variability and complexity becomes less important. Overall trends and general relationships, which are sufficient to describe the significant interactions between and among model populations (Guerrin and Dumas, 2001), also emerge. In addition to these advantages, QR presents an approach for discovering and discussing the causal evolutions of system behavior and potentially divergent paths of a system. For example, it can predict the array of potential responses an ecosystem may make to management activities. This fundamental distinction of QR from common deterministic models is important because all possible outcomes provide valuable information (Guerrin and Dumas, 2001), particularly for ecosystem succession and recovery.

This paper presents a QR model developed to define and simulate changes in benthic macroinvertebrate communities located in North Carolina Piedmont streams that are responding to changes in the physical and chemical quality induced by anthropogenic activities within the watershed. It summarizes the modeled stream ecosystems, the modelling of QR to represent these systems, and the results of simulations on the QR models. By comparing the outcomes of the simulated anthropogenic activities – urbanization of forested watershed and deforestation of riparian systems – we examine the value, applicability, and limitations of QR to stream ecosystems.

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## 2. Material and methods

### 2.1. Qualitative reasoning

We adopted the compositional approach (Falkenhaier and Forbus, 1991) for developing our QR model as an aggregate of partial, reusable components (“fragments”) to define the overall modelled system behavior. A qualitative simulation model built by components explicitly represents causal relations that are used to propagate changes in dependent quantities across the modelled system. For this model, a quantity that imposes change on the system is considered a “process” while dependent quantities are classified as “conditional”. Direct “influences” and “qualitative proportionalities” express the relationships between these quantities. The compositional approach uses fragments to organize these relationships into ecologically relevant components. “Static fragments” are identified as those model components that do not change with time, while “process fragments” include the components that define the relationships in the model (Bredeweg, 1992). “Scenarios” provide the context of initial values for the quantities from which simulations progress. Once each of the quantities and relationships is defined, a simulator engine generates potential combinations of quantity values, each known as a “state.” Transitions between states are derived from user-defined rules, and the sequence that states make for a simulation is referred to as “state-transition paths”. For more detailed descriptions of QR theory and algorithms, see Bredeweg (1992) and Falkenhaier and Forbus (1991).

Our model was implemented in the graphical interface HOMER (Bessa Machado and Bredeweg, 2002), simulated with the reasoning engine GARP (Bredeweg, 1992), and inspected through VisiGARP (Bouwer and Bredeweg, 2001). Within these three respective software components, model fragments were defined, simulations were performed, and simulation results were inspected. These modelling tools (GARP, HOMER, VisiGarp) are appropriate for modeling ecosystem components for several reasons. First, due to their explicit representation of *directed* causality, these tools are distinct from traditional ordinary differential equations (ODEs) and qualitative differential equations (QDEs), which are used in other qualitative modeling tools such as QSIM (Kuipers, 1986). The positive and negative influences and proportionalities defined in GARP indicate that an ordered relationship exists (Bert Bredeweg, personal communication 2005). In contrast, ODEs and QDEs, which can be reordered without losing the accuracy of the equation, cause a loss of physical meaning of the relationship—in reality, while  $\tau = R\gamma S$ , the weight of water ( $\gamma$ ) is not determined by the shear stress ( $\tau$ ) divided by the hydraulic radius ( $R$ ) and slope ( $S$ ) of a channel. Moreover, because QR models are constructed in GARP using meaningful, hierarchical entities and quantities defined through those entities, a more transparent set of model fragments and subsystems can be delineated than those described by simply defining quantities and mathematical constraints. These hierarchical entities are an important feature of QR models, both for improving comprehension and reusability of the model fragments as part of a larger, multi-disciplinary library.

## 2.2. Characterizing the system

This QR model was built based on the study of 54 streams in the Piedmont of North Carolina, USA. This ecoregion is bounded by the Smoky Mountains to the west and the flatter coastal plain to the east, with stream systems characterized by moderate stream slopes (ranging from 0.07% to 2.67% at our sites), igneous and metamorphic rocks, and a variety of agricultural, rural, and urban activities. Study sites drained watersheds of 13 km<sup>2</sup> or smaller. Dominant land use defined rural, agricultural, and urban settings. Riparian system conditions varied from mature to immature forest, herbaceous cover, and lawn grass. Stream substrates were composed of silt, various sands, and gravels, with median particle diameters ranging from 0.01 to 32 mm. Rainfall averaged 115 cm/yr. The wettest season occurs during early autumn in the NC Piedmont after data collection was completed.

Watershed and stream corridor characterizations were performed at each of our study sites, with both qualitative and quantitative quantities measured to characterize the riparian system condition, energy processing, watershed condition, geomorphology, sediment transport, water quality, and climate (Tullos, 2005). Twenty variables were recorded at each site: riparian herbaceous cover, riparian woody cover, detrital biomass in kicknet, drainage area, Soil Conservation Service-Curve Number (SCS-CN), woody debris, volume/longitudinal profile, friction factor, D90 (the 90th percentile of the particle size distribution of the streambed), percent of particle size distribution of the streambed that is sand or finer, water slope, pool frequency ratio, riparian infiltration, hydrologic soil

group, Bank Erosion Hazard Index (Rosgen, 2001), Bank Height Ratio, Width Depth Ratio, dissolved oxygen, specific conductivity, and inches of rainfall in the previous 30 days.

Benthic macroinvertebrates, those aquatic insects living in or around the substrates of streams, were also collected at each of the study sites according to the North Carolina Division of Water Quality (NCDWQ) Qual 5 method (NCDENR, 2003). This protocol sampled various habitats by removing insects from one riffle kicknet and one sweep net collection, one fine mesh wash of rock/log, one leaf pack wash, and visual collections. Insects were picked from samples, preserved in 95% ethanol in the field, and brought back to the lab for identification to species when possible. The list of taxa generated from these collections (Tullos, 2005) provides valuable information about the quality of the stream ecosystem. These organisms were treated as the response variable for our model because (1) they have been shown to consistently respond to the stresses contributed by changes in land use (Lenat and Crawford, 1994) and (2) they have shown sensitivity to complex ecological disturbances that are not well detected by chemical or physical indicators alone when used in isolation (Ohio EPA, 1990).

## 3. Results

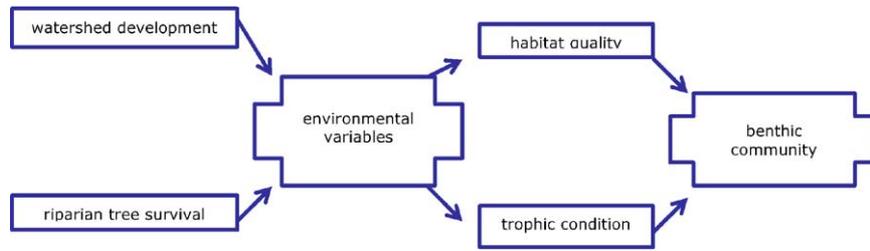
### 3.1. Developing the QR model from the conceptual model

The model was first designed conceptually (Fig. 1), under the assumption that physical (habitat quality) and chemical (trophic condition) processes alone were responsible for effects on the benthic macroinvertebrate communities, thereby neglecting the obvious role of biological interactions. From the original twenty measured variables, those determined to have significant relationships were used as “quantities” in the model to define the following effects: (1) habitat quality—median diameter of the streambed particle size distribution, detritus, woody debris, water temperature, stream-bank erosion, effective discharge, and sediment load; (2) trophic condition—canopy cover, detritus, and nutrient load.

To convert the conceptual model into a QR model, we defined relationships between quantities characterizing the watershed and river corridor using notation native to QR. These relationships were implemented through the use of direct influences (I+ and I–) and qualitative proportionalities (P+ and P–), both applied to represent the mathematical functions and causal dependencies of the system. Direct influences identify the derivative of a dependent quantity based on the value of a higher, independent process quantity. Qualitative proportionalities, also called “indirect influences”, represent the monotonic dependence between quantities, characterizing the change in value of a dependent quantity based on the change in value of a higher quantity.

### 3.2. Describing ecological relationships and knowledge representation

Preliminary analyses of the dataset, using linear regression and t-tests (Tullos, 2005), indicated that relationships between quantities could only be identified at a qualitative level. As



**Fig. 1 – Conceptual model—the conceptual model illustrates the cascading effects of development and deforestation on the benthic community through degradation of habitat quality and trophic condition.**

pointed out by Guerrin et al. (1997), this situation is common in ecological datasets built on field measurements. For example, while our dataset demonstrates a positive effect of canopy cover on the amount of detritus captured in the stream, the strength of the relationship between canopy cover and detritus is weak. As revealed by our analyses, this weakness in relationship is likely obscured by the significant and critical role of retentive features, such as woody debris and boulders, in preventing washout of detritus. This example is one of many that demonstrates the complex, highly variable, and nonlinear nature of the data. Despite these drawbacks in quantifying the study system, our field data do provide valuable information regarding the inexact nature of the interactions between quantities.

Drawing upon the information from these preliminary analyses, we expanded the QR model to (1) build the qualitative relationships between quantities and (2) evaluate appropriate landmarks for the quantities. For defining the positive or negative relationship between two quantities, we applied linear regressions, using t-tests to evaluate if these relationships were significant. We defined the modelled system by quantities with significant relationships (Table 1), using those relationships to define the positive and negative influences and proportionalities between quantities in our model fragments.

Defining landmarks for a riparian system model is problematic. For example, with intensified runoff from an

urbanized watershed, stream banks erode in response to increased sediment transport capacity in the channel. Since the specific value of hydraulic instability potentially varies for each stream and river within a system, unique landmarks should be defined for each channel. However, determination of this specific value of instability is data and resource intensive (FISRWG, 1998). It is also incongruent with the objectives of this model. Additionally, preliminary analyses indicated that reliable landmarks could not be defined by our dataset. To address these complications, we defined quantities by referencing values to an abstract landmark for a stable system. For qualitatively simulating river-corridor responses, we found our definition of an abstract landmark of the normal, stable discharge to be sufficient. Similar logic led our selection of abstract landmark definitions for the benthic community response, which we modelled to represent biological feedback in terms of tolerance or intolerance to altered habitat and trophic conditions. With the continued debate over how to classify desirable benthic communities (Karr and Chu, 1999), we found an abstract landmark for the ecological response variable to also be appropriate for our QR model.

**3.3. Model structure**

Working from the foundation developed with the numerical dataset, fourteen quantities were used in the QR model,

**Table 1 – Quantities used to describe model structure**

Quantities	Functional definition	Quantity space
Benthic community	Conditional	Tolerant, mix, intolerant
Canopy cover	Conditional	Reduced, normal, increased
Median diameter	Conditional	Reduced, normal, increased
Detritus	Conditional	Reduced, normal, increased
Woody debris	Conditional	Reduced, normal, increased
Water temperature	Conditional	Reduced, normal, increased
Streambank erosion	Conditional	Reduced, normal, increased
Nutrient load	Conditional	Reduced, normal, increased
Effective discharge	Conditional	Reduced, normal, increased
Sediment load	Conditional	Reduced, normal, increased
Riparian-tree survival	Process	Minus, zero, plus
Physical habitat stability	Process	Minus, zero, plus
Trophic shifts	Process	Minus, zero, plus
Watershed-development	Process	Minus, zero, plus

Model quantities representing relevant features of a watershed and stream corridor with their associated functional definition and quantity space (or potential qualitative values).

including four process rates and 10 conditional, or dependent, quantities (Table 1). Of these quantities, three quantity spaces (QS) were applied as series of open intervals and abstract landmarks in the form of {interval, point, interval}. One QS was defined for the process rates, one QS for the conditional quantities, and a unique QS for the benthic community response (Table 1). The {minus, zero, plus} QS for process rates refers to the operative condition of the influence, i.e., it defines negative, positive, or no change in dependent quantities. The values of the conditional quantities were defined by a {reduced, normal, increased} quantity space. The benthic community was represented as {tolerant, mix, intolerant} to represent the sensitivity to habitat quality and trophic conditions. While conceptual in the distinction between values, these quantity spaces differentiate a quantity from being in a normal, stable state versus in a positively (or negatively) altered state.

These 14 quantities define eight total fragments in the compiled model. Two static fragments – “stream” and “watershed” – define the constant relationships between quantities in the modelled ecosystem. Six process fragments model the relationships between the two static fragments and also allow progression of the modelled system as follows. Two process fragments define the impacts of watershed development and riparian condition on specific quantities characterizing the stream or watershed. A third process fragment then summarizes how the quantities affected by watershed and riparian conditions translate to the dominant energy resource (trophic condition) in a stream. A fourth fragment defines how these same quantities indirectly influence the quality of habitat (habitat stability) in the stream. Finally, two process fragments propagate the preceding indirect influences on trophic condition and habitat stability to effect changes on the benthic community composition. Defining relationships in this way allows the user to interpret the mechanistic properties of watershed activities and riparian deforestation by distinguishing habitat degradation from manipulation of trophic condition.

### 3.4. Modelling effects of anthropogenic activities

The process “watershed-development” refers to effects of urbanization of unforested, natural areas, and the consequential increases in fertilization, construction, and impervious surfaces. These effects were modelled as a positive influence on nutrient and sediment loads, water temperature, and effective discharge, all of which indirectly affect the value of median diameter of the streambed particles and streambank erosion. These environmental quantities subsequently and indirectly influence both trophic condition through increases in nutrient load and habitat stability through increases in sediment load, water temperature, and effective discharge, median diameter of the streambed particles, and streambank erosion.

Deforestation of riparian areas is represented in this model by a decline in “riparian-tree survival”. This quantity serves as an indicator of the presence and maturity of woody riparian vegetation in the area adjacent to the channel. Changes in riparian-tree survival lead a cascading series of effects on the system. Vegetation decline decreases (1) the ability of the riparian area to reduce excess nutrient loads from surface water, (2) the stability of stream banks, and (3) the supply

of detrital biomass, canopy cover, and woody debris entering the channel. As these quantities decrease, they cause changes in streambank erosion, detrital biomass, presence of woody debris, sediment load, water temperature, and median diameter of the streambed particles. In turn, changes in nutrient load, detrital biomass, canopy cover, and habitat stability indirectly influence trophic condition.

In this QR approach, the watershed-development and riparian tree survival scenarios provide the initial qualitative values from which the simulation evolves. To explore their effects on a stable watershed, we formalized initial conditions through the following quantity assignments:

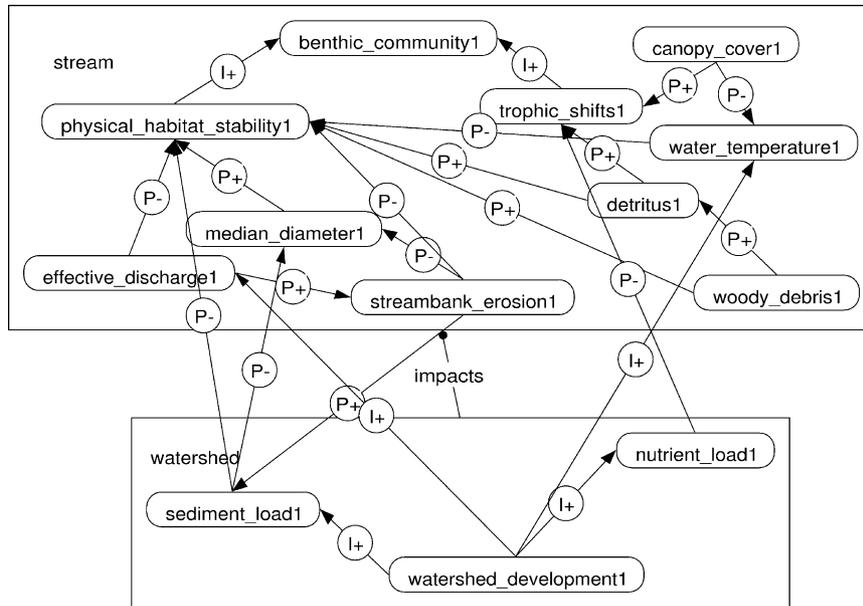
- the benthic community was assigned an initial value of intolerant from the {tolerant, mix, intolerant} quantity space,
- all other dependent quantities values were designated values of normal from the {reduced, normal, increased} quantity space,
- the active process for each of the two scenarios, watershed-development (scenario 1) and riparian deforestation (scenario 2), was assigned the value plus from the {minus, zero, plus} quantity space to initiate direct and indirect influences affecting system quantities.

### 3.5. Simulations results

Value history diagrams, representing the set of values each quantity can hold according to the transition rules defined in the model, display how quantities changed as the modelled system evolves. For our watershed-development and deforestation scenarios, two value histories are provided to illustrate system dynamics: (1) the minimum path through the system and (2) an uncondensed path that illustrates an alternative transition of the values through the system. Both are correct predictions based on the transition rules set in the development of the model.

The watershed-development simulation (Fig. 2) generated 65 states including one single initial and one final state (Fig. 3). Fig. 4(a and b) illustrates the state-transition paths. As expected, a decrease in habitat quality is seen in these simulation results as a consequence of increases in water temperature and effective discharge, with a consequent decrease in median diameter of the streambed particles. Increases in sediment load and streambank erosion reflect a response to increases in discharge within the channel. These changes in the aquatic ecosystem cause degradation to the physical conditions affecting benthic macroinvertebrates by scouring bed habitats, removing bank habitats and sediments, and creating conditions for oxygen depletion. A decline in the natural energy cycle of the ecosystem is reflected by degradation of the trophic condition, a response to increased in nutrient load.

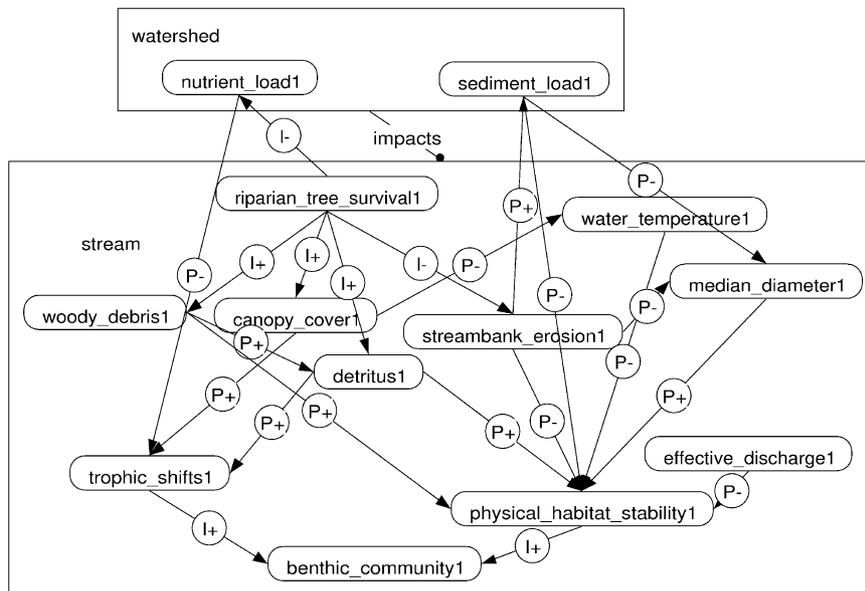
The model portrays the aggregation of these influences as a consequential shift toward tolerant benthic communities in the final state, which was the same for all state-transition paths. For our North Carolina study sites, the shift in community tolerance was demonstrated as follows. Of the stream sites in rural, predominantly forested watersheds, 91% were dominated by intolerant taxa, commonly assigned to



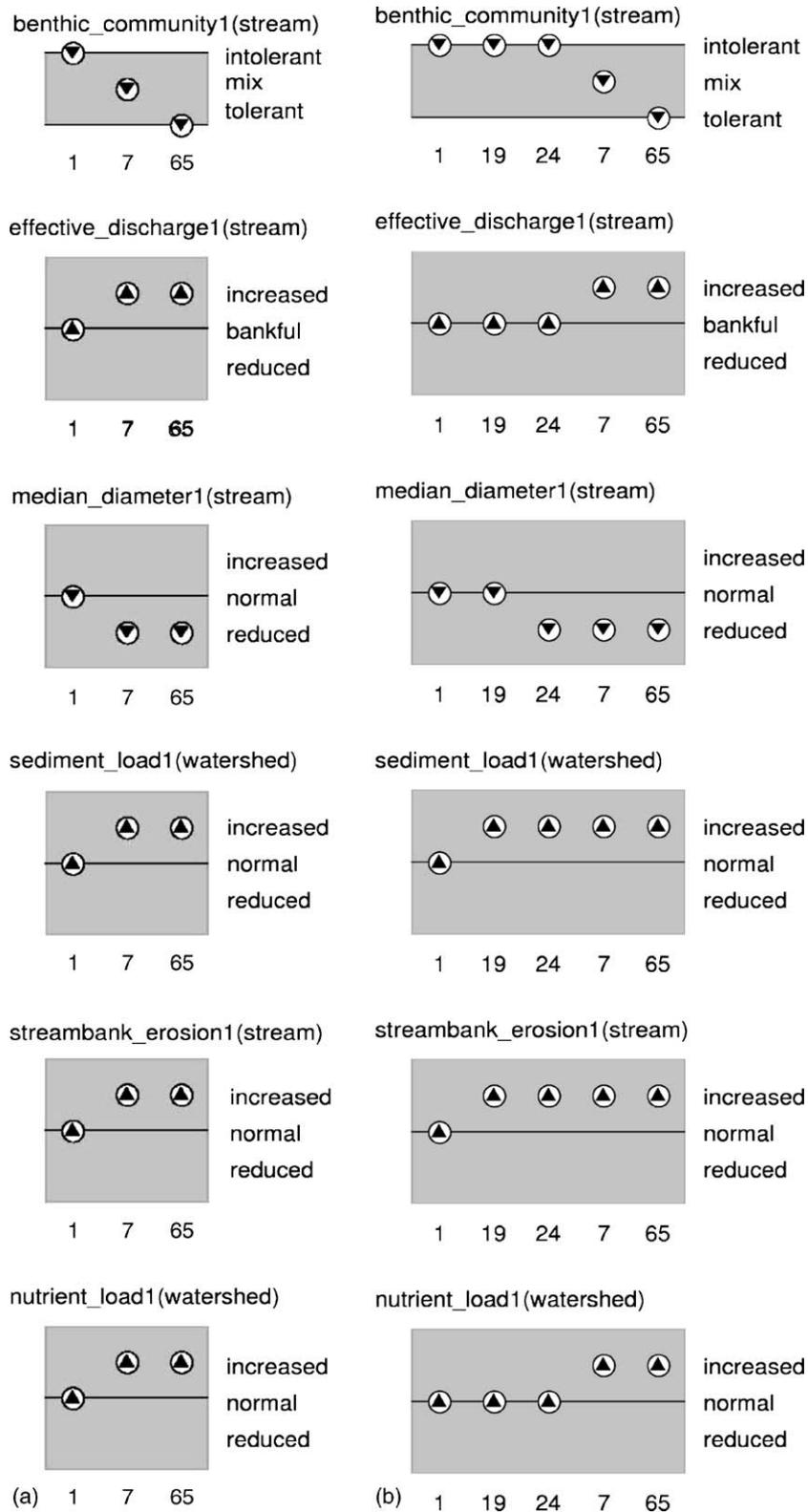
**Fig. 2 – Causal dependencies for watershed-development—this model applied 23 relationships to define the direct and indirect influences of watershed development. For example, watershed-development has a direct and positive influence on sediment load, with the practical meaning that an increase in sediment load is likely to occur when construction activities expose soil to overland erosion. Qualitative proportionalities represent the transfer of indirect influences onto subsequent quantities. For example, an increased sediment load causes fine materials to settle along the streambed habitats, represented in this figure by a negative proportionality between sediment load and the quantity representing physical habitat quality.**

the stonefly (Plecoptera), caddisfly (Trichoptera), and mayfly (Ephemeroptera) orders. In contrast, intolerant taxa dominated in 38% of agricultural watershed and 44% of urban watershed sites, respectively (Tullos, 2005). Dominant, intolerant

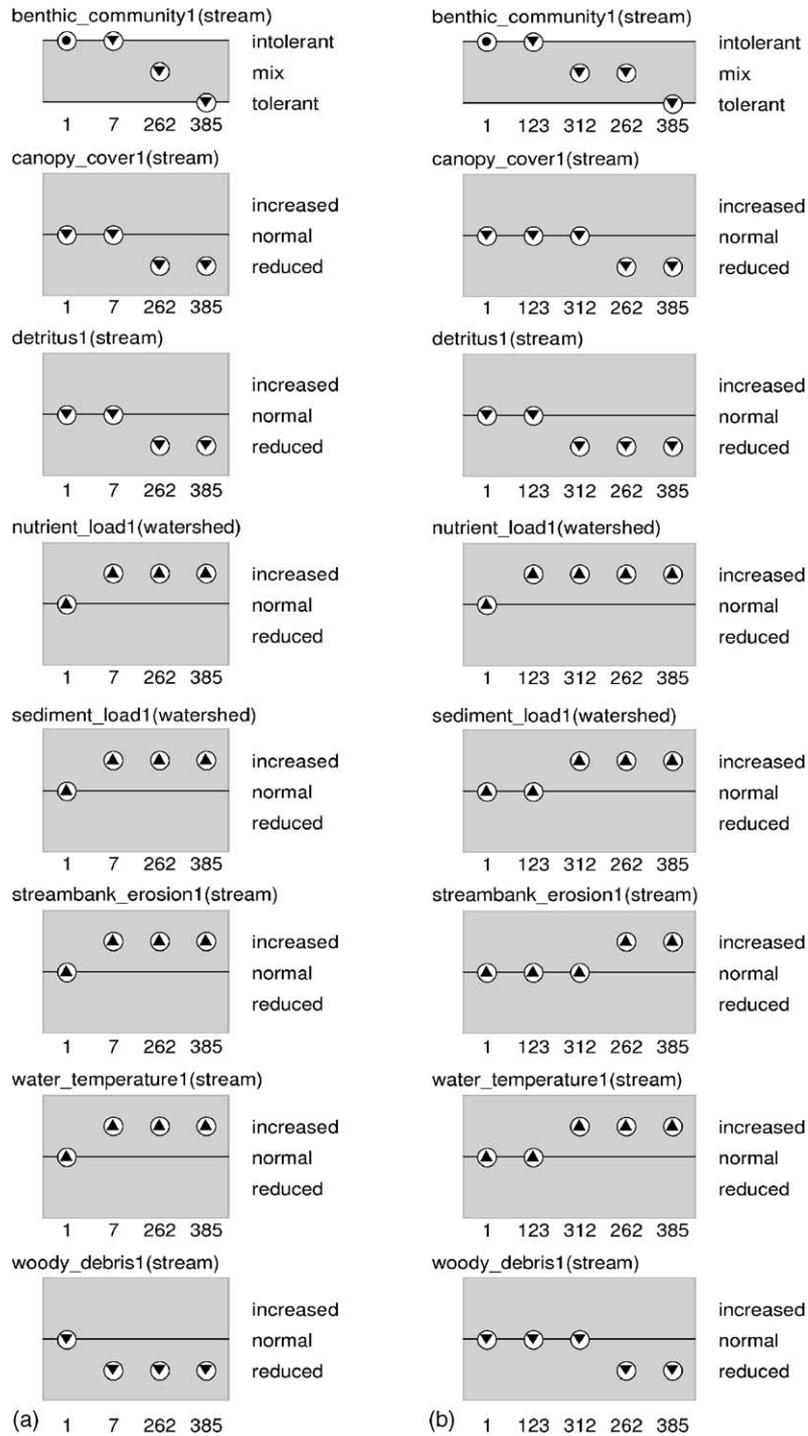
organisms were replaced by more tolerant ones, such as Chironomids in agricultural areas and Oligocheata in urban areas, both of which are more adaptable to degraded conditions.



**Fig. 3 – Causal dependencies for riparian deforestation—this model applied 18 relationships to define the direct and indirect influences associated with deforesting a riparian area. For example, detrital biomass serves both as a habitat substrate for benthic macroinvertebrates (Quinn and Scarsbrook, 2001) and a fundamental feature of the trophic condition of river ecosystems (Vannote et al., 1980). Canopy cover affects the amount of sunlight available for photosynthesis, which influences trophic condition (Bunn et al., 1999), while also affecting physical habitat stability by regulating water temperature (Platts and Nelson, 1989).**



**Fig. 4 – (a and b) Value history for watershed development. Value history (a) represents the most condensed transition path from the first to the final state. Value history (b) illustrates a longer path, with the intermediate steps demonstrating an alternative transition of states. The positive watershed-development process consequently affected six quantities in this simulation. The pattern of “benthic community” shift is similar for both value histories; the quantity remains in the “intolerant” interval until all quantities become steady in their ultimate intervals.**



**Fig. 5 – (a and b) Value histories for riparian deforestation. Value history (a) represents the most condensed transition path from the first to the final state. Value history (b) illustrates a longer, alternative transition of states. Eight quantities were consequently affected by the positive riparian deforestation process, illustrating a slightly greater complexity in this model when compared to the six quantities affected by watershed-development. In (a) and as with the watershed-development scenario, the ‘benthic community’ remains within its original quantity interval until all other quantities have moved through the quantity spaces. However, (b) demonstrates a divergence from this pattern, where the benthic community moves into the ‘mix’ interval while higher influencing quantities (canopy cover, streambank erosion, and woody debris) are still changing quantity spaces. These three quantities are directly influenced by the process “riparian-tree survival” and thus continue to change beyond the first step.**

The riparian deforestation simulation illustrates community response toward tolerant benthic macroinvertebrate taxa or toward species that can survive under increased fine sediment levels, warmer waters, decreased supply of detrital material and woody debris, and the autotrophic conditions associated with higher nutrient loads. This scenario generated 385 states, significantly more than the watershed-development scenario. Both scenarios also generated a single initial and a single final state. In our watershed-development model, habitat degradation resulting from removal of the riparian forest was expressed (Fig. 5a and b) as decreases in canopy cover, detritus, woody debris, and median diameter of the stream bed particle size distribution, and increases in sediment load, streambank erosion, water temperature, and effective discharge. Trophic conditions were indirectly influenced by increases in the nutrient load and decreases in the canopy cover and detrital material. The effects of these simulated changes in abiotic features of the river corridor resulted in a consequential shift of the insect communities toward the intolerant value in the {tolerant, mix, intolerant} quantity space.

## 4. Discussion

### 4.1. Application of QR models to stream ecosystems

Benthic macroinvertebrate communities have long been recognized for their significant role in stream ecology, high natural variances of field data, effects of scaled responses, and fragmented and limited datasets make prediction and global analysis of stream ecosystems difficult to reliably and consistently accomplish. While reputable numerical models exist for studying stream ecosystems, such as RIVPACS (Wright, 2000), AUSRIVAS (Davies, 2000; Simpson and Norris, 2000), BEAST (Reynoldson et al., 2000), and PHABSIM (Waddle, 2001), the application of QR models in stream-ecology studies is a new approach. They offer the advantage of providing explicit causal linkages between watersheds and stream ecosystems without the necessity of well-defined numerical relationships or distributional assumptions. In the field of ecological restoration where prediction of potential trajectories is a fundamental and debated necessity (Temperton et al., 2004), QR models offer an opportunity for forecasting potential ecosystem responses to various anthropogenic activities.

Application of QR to ecological evaluation and prediction is not a new concept. Many researchers (Kamps and Peli, 1995; Guerrin, 1991; Guerrin and Dumas, 2001; Salles and Bredeweg, 1997; Salles and Bredeweg, 2003; Salles et al., 2003a,b; Rykiel, 1989; Rickel and Porter, 1992; Wolfe et al., 1986) have demonstrated the usefulness and application of QR as educational and predictive tools. Drawing upon the concepts developed by these existing applications, we offer a new approach based on field observations that takes the QR model a step further. Our model can explicitly characterize the features and interactions between physical stream and benthic macroinvertebrate communities, which distinguish riparian ecosystems. By using defined qualitative relationships, a common feature of ecological systems (Lisle and Lewis, 1992), our model can

demonstrate how manipulation of watershed and stream corridor features may affect benthic macroinvertebrate communities.

Although validation of QR models has been recognized as a limitation, the variability associated with numerical data suggests that true validation of any global model is an uncertain endeavor (Guerrin and Dumas, 2001). Using the compositional approach for building model complexity by parts does lead to a validation process by which the model is tested against a reference of domain knowledge (Rykiel, 1996). In this respect, our model corresponds to the current understanding (Bunn et al., 1999; FISRWG, 1998; May et al., 1996; Naiman and Bilby, 1998) of the effects of watershed-development and riparian deforestation on benthic macroinvertebrate communities.

### 4.2. Distinctions in simulated outcomes of two anthropogenic activities

Simulation results for the model scenarios – watershed-development and riparian deforestation – demonstrated a common shift toward benthic community tolerance. For our model, differences in path lengths or transitions do not represent meaningful disparity between the simulations. The simulator simply generates all possible paths through the specified transition rules. In our view, differences of quantity transitions do not appear to be of consequence. However, important distinctions between the two scenarios do exist and are illustrated by: (1) the initial state values, (2) the distinction of dominant processes between the two activities, and (3) the number of states generated by the simulation. Comparison of the simulation results between the two scenarios demonstrates an interesting difference in the first state predicted by the simulations. The watershed-development scenario generated an initial benthic community that was immediately affected by the influences on this activity. In contrast, the riparian deforestation scenario generated an initial state where the conditional quantities responded, but the benthic community remained unaffected at the value “intolerant.” This sequence creates a longer minimum path for the riparian deforestation model. It also suggests a more indirect effect of riparian deforestation on the benthos as the simulator resolves the influences.

These simulations also reflect a distinction in the processes or mechanisms by which development of a watershed and deforestation of a riparian area affect benthic macroinvertebrate communities. In the watershed-development simulation, the quantities affected were most frequently associated with habitat characteristics, having with only a single quantity reflecting change in the trophic condition. The lack of indirect influences through trophic condition suggests that the effects of urbanization on benthic macroinvertebrate communities are primarily through degradation of habitat quality. In contrast, the riparian deforestation model demonstrates influences of multiple quantities on both habitat stability and trophic condition. Accordingly, the deforestation scenario creates considerably more potential combinations of values than does the watershed-development scenario, revealing an increased complexity of trophic condition influences and an associated larger state-transition graph.

### 4.3. Utilizing QR models for stream ecosystem analysis

The utility and uniqueness of our model is in the analysis of stream ecosystem restoration and management. Two elements that are particularly relevant and important to this field emerge from this model: (1) the existence of thresholds in ecosystem response and (2) the identification of gaps in fundamental knowledge about these systems.

Both scenarios demonstrate the existence of thresholds in the succession of modelled quantities. The entire set of simulated solutions hold the quantity “benthic community tolerance” at the value “intolerant” until all influencing quantities have reached their ultimately degraded value. At this point, the benthic community value moves across the landmark value in the center of the quantity space, and subsequently to the tolerant value, where the simulation ends. For the developing watershed scenario, this effect is illustrated by the simulation of the quantities crossing state 7 before reaching the final state numbered 65. Similarly, in the riparian deforestation scenario, the sequence reaches state 262 before ending the simulation at state 265. As defined by Eisenack and Petschel-Held (2002), these states represent locked sets {7, 65} and {262, 265} for the watershed-development and riparian deforestation simulations, respectively. States 7 and 262 serve as strong attractors for the final states in the two simulations, indicating that the system is evolving toward an irreversible trajectory. In our model simulations, these locked sets are important because they demonstrate an identifiable limit in the underlying system, indicating a boundary at which the system moves toward an indelible condition. The implication of the locked sets for watershed and riparian management is in the need to control the effects of anthropogenic activities before some degradation threshold of ecosystem services is reached. Beyond an ecosystem’s resiliency to degradation, the opportunity for restoration of ecosystem services may not exist (Temperton et al., 2004).

As with other models, our QR approach presents a simplification of stream ecosystems with implicit limitations in representing the complexity of natural systems. Among our model’s limitations is the simulation of ambiguous paths that are difficult or sometimes impossible to interpret. The increase in number of qualitative solutions with an increase of quantities is a common limitation in developing global models of complex systems (Eisenack and Petschel-Held, 2002; Guerrin and Dumas, 2001). In the case of our model, the generation of 357 states in the riparian deforestation simulation indicates a substantial increase in the ambiguity of this scenario over the developing watershed scenario. This ambiguity does not represent erroneous simulations. Instead, it actually characterizes a lack of restricting definitions defined in a model of this kind, producing excessive but acceptable predictions (Salles and Bredeweg, 2003). For our model, the simulated ambiguity reflects a lack of constraint in defining the relative influence of the quantities on each other and on the benthic community.

Reducing ambiguity in qualitative models is accomplished both by constraining quantity spaces and by using correspondences and inequalities to represent the relative amounts of direct and indirect influences. One of our modeling assumptions was to set all influences equal. As is often the case, this decision was justified by a lack of documentation for defining

the correspondences between quantities (Guerrin and Dumas, 2001), thereby avoiding the subjective and region-specific definition of the relative importance of different habitats and stressors on benthic communities. While ambiguity is not typically a desirable feature of QR models because it limits the interpretability of larger models, study of ambiguity in QR models such as ours may be used to direct research toward improving our understanding of the modeled system. For example, does water temperature have a greater effect on benthic macroinvertebrate communities than does the nutrient load? Is the combined effect of increased effective discharge and erosion of stream bank habitats more detrimental to macroinvertebrate survival than embedding habitats of streambed substrates with fine sediments? Such questions are useful for prioritizing research and management options. Defining these types of relationships will identify governing mechanisms, a necessary task for developing predictive tools for riparian ecosystems.

## 5. Conclusions

This model establishes a framework for discussing and evaluating the responses of benthic macroinvertebrates to anthropogenic activities. Building on this framework, numerous other models may be developed for improving understanding and management of river systems. As part of a larger stream ecosystem library, the fragments developed for this model can serve as fundamental building-block components for larger, context models. For example, this model excluded predation, competition, distance to recolonization source, and other factors that undoubtedly influence benthic communities. These interactions were omitted in an effort to isolate the impacts of anthropogenic activities on stream benthos and simplify model interpretation. Adding them in by drawing upon population dynamic model libraries (Salles and Bredeweg, 2003) would expand our model to evaluate how biotic interactions change the outcome of anthropogenic activities.

In another respect, the model fragments defined here provide the foundation for predicting how mitigating activities may affect the response of benthic communities in disturbed systems. Addition of agent fragments, known as “model actors that enforce changes upon a system” (Bredeweg, 1992), to the existing fragment library may provide insight into the effectiveness of defined management options (e.g., stream restoration, stormwater management, and riparian revegetation) for enhancing benthic integrity (Tullos, 2005). Thus, the development of QR simulations as decision-support tools has significant potential for poorly defined systems (Brajnik and Lines, 1998). Clearly, protecting our complex river systems requires reliable prediction models to support management and policy evaluation.

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