Development of a Qualitative Model for Investigating Benthic Community Response to Anthropogenic Activities

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Abstract

The quality of stream ecosystems in many areas of the world is significantly degraded as a result of conversion of natural landscapes to urban and agricultural uses. Impacts of these activities can be observed in the organization of the benthic macroinvertebrate communities, which have distinct responses to physical, chemical, and biological disturbances. However, the information relating anthropogenic activities to benthic communities is fragmented and temporally inconclusive. Qualitative reasoning introduces a technique for resolving these deficiencies and increasing the understanding and prediction of stream ecosystem quality and function. By modeling these complex systems qualitatively, we develop a comprehensive understanding of the underlying processes that control benthic communities and thus provide a tool for education and minimization of the impacts to these sensitive systems. This study summarizes the development of this qualitative model for describing the impacts of watershed development and riparian deforestation activities on benthic macroinvertebrate communities. The model provides insight both into the response of stream ecosystems to destructive watershed activities and how restoration can assist in their recovery.

Introduction

Luna Leopold stated that "the health of our waters is the principal measure of how we live on the land," and history has demonstrated that increased productivity of our lands and natural resources has been a priority over water quality. This comes at a large cost to natural systems, and it is only in very recent history that we have begun to realize the impacts our activities have on ecological functions, as the insults to these ecosystems have exceeded their natural resilience to disturbances.

Development impacts stream ecosystems in several ways. As forested watersheds urbanize to accommodate the residential, commercial, and industrial needs of a community, the volume, frequency, and intensity of peak storm events increase through reduced infiltration in the watershed. Many times, these larger flows carry higher sediment loads from construction runoff and increase the loss of soil from streambanks through erosion. Degradation of the riparian condition is also responsible for losses to stream quality. Deforesting these areas results in higher sedimentation of benthic habitat, reduced supply of Large Woody Debris (LWD) and detrital matter, increased water temperature, and decreased ability of the riparian system to remove nutrients from stormwater runoff.

The effect of these activities on benthic communities is of great significance as the number of remaining high quality streams rapidly diminishes. It is crucial to develop accessible knowledge concerning both the value of the lost function of streams and the potential that responsible development can provide to stream ecology. David Montgomery states that 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" (Montgomery 2001). Qualitative Reasoning (QR) provides an opportunity for effectively accomplishing this level of understanding. It satisfies the need for aggregation, articulation, and calculation of well-accepted but abstract ecological theories that are not empirically supported with long-term data, as is common in ecological systems. The proposed qualitative model, in an attempt to resolve these concerns, was developed to describe and predict changes in benthic communities in response to changes in the physical and chemical qualities of a stream ecosystem induced by anthropogenic activities. Further, by emphasizing and presenting the benthic response in an illustrative manner, stream restoration designers interested in more holistic approaches can use this model to visualize the causal evolutions of ecosystem behaviors induced by their designs.

Background

Natural streams host a substantial diversity of aquatic insects, which are critical as a base component to the larger food chain. Specifically, the benthic macroinvertebrates, those sediment-living organisms which can be identified with the naked eye and which lack a backbone, are well-recognized indicators of the function of the wider stream ecosystem. Aquatic organisms have shown sensitivity to complex ecological disturbances not well detected by chemical or physical indicators alone (Ohio EPA 1990). Particularly with respect to environmental effects over time, the ability of a stream benthos community composition to reflect the integrated impacts of a watershed is great. Unfortunately, although a very large amount of data exists on these organisms in a wide range of geographical regions, the datasets are often scattered, fragmented, and span only short time periods. These partial datasets do however provide the foundation for a vast domain theory of stream ecosystems. While it is well known that diminished biological diversity results from a history of channel straightening, dredging, damming, development, and pollution, the task of unifying these concepts into a comprehensive and explicit representation remains. Development of a model to accomplish this would provide insight into the impacts human activities can have on stream ecology and assist development of alternative solutions to minimize destruction of these irreplaceable systems.

We propose that this task can be accomplished through QR models. The first step is to describe the system to be modeled in terms native to the domain theory of stream ecology. Then, the qualitative model is built as these terms are translated to the language of QR. Here, we give a brief background on the language of QR, and then describe the stream ecosystem and how QR is used to define it.

Using QR to define the system.

The technique taken for defining this system is described as the compositional approach (Falkenhainer and Forbus 1991), which involves the development and aggregation of smaller, partial system behavior components to describe overall system behavior. We identify the *static fragments*, or those model components that do not change with time, and the *process fragments*, those that define the relations between static fragments and advance the evolution of the system. We then represent the domain theory of stream ecosystems in the QR language of causal dependencies established by the qualitative process theory (Forbus 1984). Finally, GARP is used to generate simulations to "explain the behaviors of populations in terms of the basic processes that determine it" (Forbus 1984).

Through Qualitative Process Theory (QPT), we have structural definitions of how quantities and processes interact. These causal relationships are characterized by direct and indirect influences. Direct influences initialize system evolution through a process. These rates are symbolized in GARP (Bredeweg 1992) by +I and –I, to represent a positive or negative influence on a dependent variable. In contrast, indirect influences, known also as proportionalities, are used to propagate changes initialized by the direct influence to another dependent quantity. Like influences, proportionalities can be either positive or negative, and relate monotonic changes of a dependent quantity to changes in an independent quantity. For example, an increase in watershed development, a rate, has a positive *influence* on sediment load, which in turn has a negative *proportionality* to habitat quality. Using these representations, the above causal relationships of watershed development on bug community can be described symbolically as I+(sediment load, watershed development), P- (habitat stability, sediment load), and I+(bug community, habitat disturbance), to describe the positive influence of watershed development on sediment load, the negative proportionality of sediment load to physical habitat stability, and the influence of habitat stability on bug community. This notation will be used throughout the paper to define the causal relationships between quantities in the model, with details of the system quantities discussed in the following section.

The qualitative values that a quantity can hold are described by quantity spaces, defined in sets of alternating points and intervals. Examples include {zero, plus} and {min,plus,max}, meaning that values can either hold the point 'zero' or the interval 'plus', and a value can hold the point 'min', the interval 'plus', or the point 'max', respectively. Then, to define the condition of a quantity at some state in the model, either initial or simulated, values are symbolized by a magnitude-derivative pair <magnitude,derivative>. For example, the quantity nutrient load = <normal, + > indicates that the state variable "nutrient load" has the qualitative value 'normal' and is increasing, as may be the case with a riparian system that is being deforested and losing its ability to remove nutrients from stormwater runoff.

More detailed descriptions of qualitative process theory can be found in several sources (Bredeweg 1992, Forbus 1984). This brief summary is provided for communication of the causal relationships used to define this system in QR language. Models were built using the graphical interface HOMER (Jellema 2000, Bessa Machado and Bredeweg 2002), simulated within the reasoning engine GARP (Bredeweg 1992), and inspected within VisiGARP (Bouwer and Bredeweg 2001). Within these three components, model fragments are defined, simulations are performed, and simulation results are inspected. We now define the modeled system and describe how it was represented in this QR language for model simulations, then discuss the modeling results for two scenarios.

Defining the System in Natural and QR Languages

It is widely recognized that the benthic macroinvertebrate community composition responds consistently to the stresses contributed by changes in land use (Lenat and Crawford 1994, Lemly, D 1982). As land uses are converted, sensitive species, such as stoneflies, caddisflies, and mayflies, which are abundant in undisturbed and forested watersheds, are replaced by insensitive taxa adapted to degraded conditions, such as chironomids in agricultural areas and oligocheates in urban areas. By describing the causal relations that result in these community shifts, efficient approaches for minimizing and mitigating the impacts of these land use burdens on stream ecology can be developed.

First, we define the structure of the system to be modeled. It is important to note that we chose the fewest possible quantities to comprehensively characterize the function of these systems. Results from ordination analyses suggesting which variables are most responsible for community composition in these systems (Tullos et al 2004) were used to define the minimum modeling components. Addition of quantities and increasing model complexity, though natural for describing these complicated systems, may result in loss of information in interpreting causal chains and simulation results. These components and their interactions within stream ecosystems are described below.

The quantity 'bug community' refers to the composition of benthic taxa, described here by their tolerances to instream energy and habitat conditions. 'Detritus' is an essential component to the energy processing of stream ecosystems, and has been shown to be one of the most significant environmental factors contributing to community composition of benthic macroinvertebrates (Tullos 2004). 'Large Woody Debris' (LWD) frequently supports a high density of aquatic macroinvertebrates through its role of energy resource supply for the many organisms that graze on periphyton thriving on its surface, as well as serving as refugia during high flow events when the streambed is mobile (Sweeney 1992). 'Water temperature' tolerance thresholds exist for benthic organisms, beyond which communities will shift to decreasing sensitivity. The loss of sensitive benthos with water temperature increases is well recognized, and is a result of both the removal of shading riparian tree canopy adjacent to the stream and increases in heated impervious surfaces within the watershed (Sweeney 1992). Increases in 'nutrient loads' delivered by the watershed result in decreased diversity and, when combined with tree canopy removal, can significantly alter the nutrient cycling of stream ecosystems. 'Flow regime' has been found to be an important contributor to benthic community loss in headwater streams (Tullos 2004), damaging and removing aquatic habitat as a result as pervious surfaces are converted to imperviousness during urbanization. Widely recognized as America's leading pollutant, unbalanced transport of 'sediment loads' contributed by the watershed and streambanks is often responsible for increased embeddedness of stream substrates, increased stream turbidity, and development of levees along stream banks restricting critical floodplain access. 'Watershed development' is one activity common to all ecoregions in most of the world, and results in increased sediment and nutrient loads, peak flows, and 'streambank erosion', leading to degradation of habitat quality for aquatic insects. 'Riparian tree survival' refers to those areas adjacent to streams which support ecological characteristics of energy flow, nutrient cycling, water cycling, hydrologic function, and plant and animal population. These areas are known to reduce excess nutrients and sediments from surface water, as well as reducing peak flows provided by the watershed, through infiltration, interception, and transpiration of the vegetation.

Formally, two processes influence the evolution of stream ecosystems. The first is 'physical habitat stability,' which refers to the responsibility of physical processes within the watershed controlling the stability or disturbance of natural stream habitat. The physical quantities in this model used to describe this disturbance regime include sediment load, peak flow, streambank erosion, and nutrient load. The mechanisms by which these variables impact habitat are defined by QR relationships in Table 1. The second process is described by 'trophic shifts,' which refers to the tendency of a system to move towards heterotrophy (a respiratory based system where energy resources are derived from organic material washed into the stream) or autotrophy (a photosynthetic system where energy resources are primarily sun dependent) in response to activities within the watershed or riparian areas. The River Continuum Concept (RCC) from Vannote et al (1980) describes this theory of energy dependency in stream ecosystems, and is structurally represented in this model using quantities such as nutrient load supplied by the watershed, and the contribution of large woody debris and detrital matter from the riparian areas. The relationships used in this model to describe the effects of these factors on trophic shifts are also described in Table 1.

Model Development and Assumptions

The philosophy taken in modeling this system is that of the greatest simplification and flexibility without loss of information. Because "there are not many obvious landmarks that uniquely characterize qualitative distinct behavior of an ecological system" (Salles and Bredeweg 2003), complexity of quantity spaces was minimized. All quantities are described by a {interval,point,interval} space. The interpretation of these is simple for most quantities, which hold the context-dependent {reduced, normal, increased} quantity space, with the exception of the processes, which are assigned the quantity space {minus, zero, plus} to indicate their direction. For clarification, the process of 'trophic shifts' actually refers to the movement of the system towards heterotrophy (plus), or autotrophy (minus), with constancy represented by the point zero. 'Physical habitat stability' is similar, with the plus interval representing the evolution towards a stable habitat, and minus indicating movement towards a more unstable habitat.

Though still an interval-point-interval quantity space, the quantity ‘bug community’ is described by unique values to illustrate the ultimate shift of the insect community towards something of greater or reduced overall function, rather than just an increase or decrease in the number of insects. In other words, it important to distinguish the type of community that survives under different stresses, not simply the number of organisms. Species richness, or the number of individuals, is a much less descriptive index of ecological function than taxa morphology or tolerance, as discussed in Diaz et al 2001. In addition, because the definition of tolerant/intolerant organisms will shift both between and within ecoregions, the characterization of bug community quantities must accommodate this user-defined flexibility, which is accomplished here by the use of tolerance rather than quantity.

The concept of direct dependence of community composition on trophic and habitat disturbance control is fundamental to this model. Certainly, there are other factors that influence community composition in stream benthos, such as predation, competition, and distance to recolonization source. Through this ‘If you build it, they will come’ approach, population recovery is expected to occur regardless of the proximity to recolonization source. Further, influences of competition and predation are neglected in this model in order to isolate the impacts of anthropogenic activities on stream benthos. Simplifying the simulation interpretation process is desirable as this educational tool is intended to elucidate how responsible design can support a stable and diverse aquatic system.

Model Fragments Library

The model is comprised of five fragments utilizing the quantities previously defined. The two static fragments are identified as ‘stream’ and ‘watershed’. The three process fragments include ‘trophic shifts,’ and ‘physical habitat stability,’ and ‘processes affect bugs.’ Mechanisms relating the three processes are summarized in Table 1 and Figure 1 below.

Table 1 – Quantities and Relationships Defining Processes

physical habitat stability			**natural meaning**
watershed development	(+I)	sediment load	a positive rate of watershed development increases sediment loads in construction and unvegetated areas.
watershed development	(+I)	flow volume	a positive rate of watershed development increases flow volume through increased impervious areas, resulting in a decrease in infiltration, local storage, and plant transpiration.
watershed development	(+I)	nutrient load	a positive rate of watershed development increases nutrient load through activities such as lawn fertilization, detergent releases, and increased human and animal waste production.
flow volume	(+P)	streambank erosion	increases in peak flow are also responsible for increases in streambank erosion, as erosive stream power and shear stress along the banks are associated with higher flows.
flow volume	(-P)	habitat stability	increases in flow volume are responsible for decreases to habitat quality, as flow-induced mortality and destruction of refugia results from these increased flows.
streambank erosion	(+P)	sediment load	sediment loads increase with streambank erosion, as bank material becomes suspended in the water with high, erosive flows.
sediment load	(-P)	habitat stability	sediment loads decrease the quality of habitat by embeddeding, or obstructing access to substrates.
nutrient load	(-P)	habitat stability	nutrient loads have increase habitat disturbance by encouraging the growth of macrophytes and other photosynthetic organisms adapted to live in high nutrient conditions.
habitat stability	(+I)	bug community	changes in the rate of habitat disturbance (modeled here as moving from a low quantity space of severely degraded to pristine) positively affect the changes in bug community.
trophic shifts			**natural meaning**
riparian tree survival	(+I)	large woody debris	increases in the rate of riparian tree survival results in increases of fallen trees and branches in the stream.
riparian tree survival	(+I)	detritus	increases in the rate of riparian tree survival results in increases of detrital matter, a necessary energy resource for heterotrophic systems.
riparian tree survival	(-I)	nutrient load	a decrease in riparian tree survival rate results in higher nutrient loads as the ability of the riparian area to capture and filter nutrients decreases with vegetation removal or destruction.
large woody debris	(+P)	trophic shifts	increases in large woody debris increases habitat for heterotrophic organisms.
detritus	(+P)	trophic shifts	increases in detrital matter are associated with shifts towards heterotrophic energy resources.
nutrient load	(-P)	trophic shifts	increases in nutrient loads are associated with shifts towards autotrophic systems.
trophic shifts	(+I)	bug community	heterotrophic systems typically support intolerant insects and conversely, autotrophic systems are known to support tolerant insects.
processes affecting community			**natural meaning**
trophic shifts	(+I)	bug community	a plus magnitude of trophic shifts indicates a trend towards heterotrophy, and a resulting trend toward intolerant insects.
habitat stability	(+I)	bug community	a plus magnitude of physical habitat stability represents a movement away from degradation, supporting more intolerant organisms.

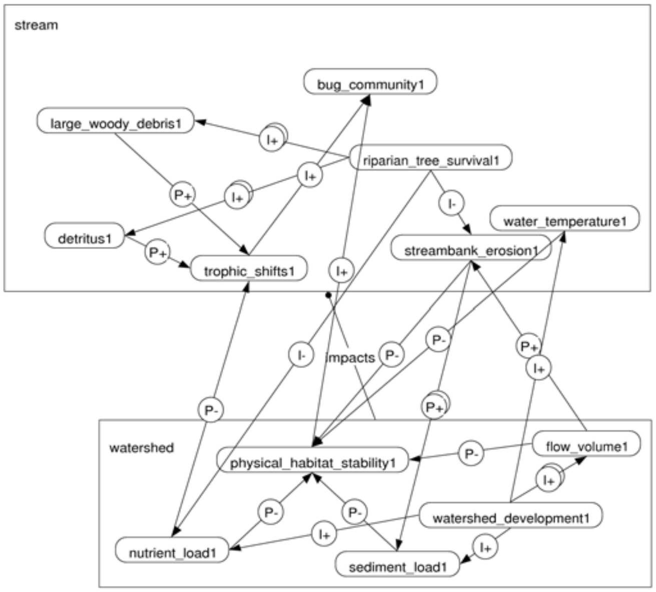

Figure 1 – Quantity Dependencies

Simulations and Results

Within the HOMER interface, scenarios are developed to provide the initial qualitative conditions of the system from which the simulations move forward. Simulations were performed for many initial conditions to test the predictive capacity of the model. Specifically, the impacts of restoration activities, installation of stormwater best management practices, urbanization of moderately developed and forested watersheds, and removal of riparian vegetation were simulated and are appropriately predicted by this model, based on our implicit understanding of benthic response to these activities. While this model does correctly forecast responses for all of the above scenarios, only two of the scenarios are discussed here; development of a forested watershed and riparian deforestation are both activities that alter some critical aspect of benthic habitat.

The first scenario, *watershed development*, results in increased peak flows, sediment loads, nutrient loads, and bank erosion, which negatively affect benthic habitat quality by removing the habitat or access to it. This scenario was modeled simulating development of a forested watershed with normal flows and minimal sediment load:

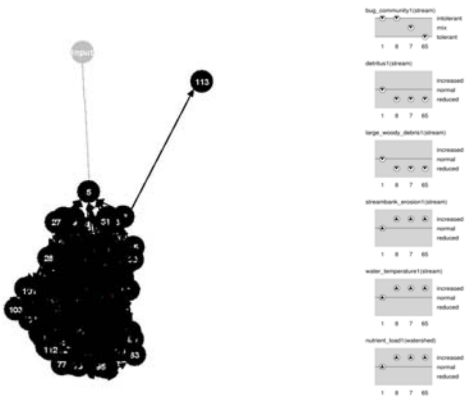

Figure 2 – State Transition and Value History Results for Watershed Development.

An illustration of the state transitions and value histories from the simulations are shown in Figure 2, above. Simulations produced 113 total states and 1 final state. As expected, a decrease in habitat quality is seen in the value histories, along with a move towards tolerant benthic communities. The numerous paths towards the single final state, shown in the state transition figure, illustrate the various routes an ecosystem can take as it responds to external pressures. These results suggest why numerical models often exhibit errors in their predictions of ecosystem response; the process interactions are neither simple nor transparent. Though the final state is the same for all paths, the length and direction of each path is distinct.

The second scenario of interest is 'riparian forest removal,' common in many agricultural areas where productivity per acre is very valuable. In this scenario, the magnitude and derivative of the rate of riparian tree survival are both set to minus, indicating that the trees are being removed, influencing the quantities defining habitat quality. State transitions and value history results are shown in Figure 3.

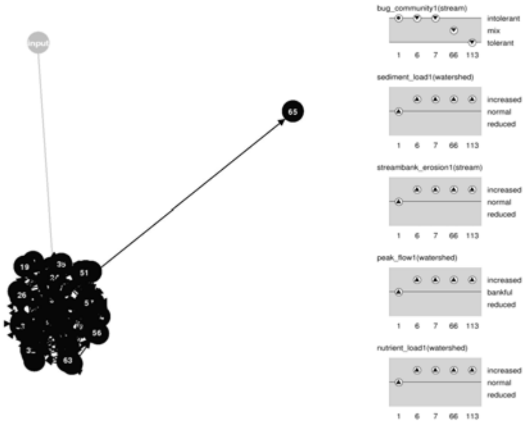

Figure 3 – State Transition and Value History Results for Riparian Deforestation.

The results show that, again, community composition moves towards tolerant taxa, or those that can survive under more autotrophic conditions with higher nutrient load and little to no organic material. Habitat degradation occurs with decreases in detrital matter input, decreases in LWD, and decreased nutrient removal (or increased nutrient load), expressed in VisiGARP as a trend towards tolerant insect communities. Sixty-five total states, with single initial and final states, were generated by GARP. The simulation of many intermediate states towards a single final state again demonstrates the various paths an ecosystem takes as it responds to external stresses and attempts to attain some form of stability. This evolution through numerous paths towards a final state emphasizes the dynamic responses an ecosystem will experience`, but also highlights the well-accepted tendency of these systems to eventually reach a single, steady state condition.

Discussion and Conclusions

The model described in this paper predicts the effects of different human activities on benthic communities. For the two scenarios discussed, many paths are simulated to describe the responses of benthos to these activities. This is as expected, considering the large number of quantities required to describe this complex system and our hesitation to include value correspondences and restrictions. To determine the impact of this ambiguity on the final state predictions, additional fragments restricting the number of states, through correspondences and inequalities of quantity space values, were simulated. These simplified models produced the same final state with significantly fewer intermediate states, indicating that the additional constraints only simplified the intermediate steps and provided no additional information for the model prediction.

We believe that inspecting the intermediate transitions is valuable to restoration designers with limited knowledge of ecosystem succession. Further, it is a constructive demonstration that the exact evolution of insect communities can vary, suggesting that over-defining and simplifying these evolutionary steps that signify valuable community responses can result in a loss of information.

In conclusion, QR of these systems provides potential for managing, mitigating, designing, educating, and researching stream ecology. These QR models can guide research direction by organizing knowledge about a system and seeing where fundamental gaps in the knowledge exist. The "explicit representations of causality that can support explanations about system's structure and behavior," provided by QR, are essential to developing holistic approaches to watershed development and restoration designs (Salles et al 2003). Constructing qualitative models such as this enables designers to visualize stream ecosystem processes for producing restoration projects with a functional biological component and for minimizing the inevitable impacts of urbanization.

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References

Bessa Machado, V. and Bredeweg, B. (2002) Investigating the Model Building Process with HOMER. *Proceedings of the International workshop on Model-Based Systems and Qualitative Reasoning for Intelligent Tutoring Systems*, San Sebastian, Spain; pgs 1-13.

Bouwer, A and Bredeweg, B. (2001) VisiGARP: Graphical Representation of Qualitative Simulation Models. *Artificial Intelligence in Education: AI-ED in the Wired and Wireless Future*, IOS-Press/Ohmsha, Osaka, Japan; pgs 294-305.

Bredeweg, B. (1992) *Expertise in Qualitative Prediction of Behavior*, Ph.D. Thesis, University of Amsterdam, Amsterdam, The Netherlands.

Diaz, S. and Cabido, M. (2001) Vive la difference: Plant Functional Diversity Matters to Ecosystem Processes. *Trends in Ecology Evolution* 16: 646-655.

Falkenhainer, B. and Forbus, K. (1991). Compositional modeling: finding the right model for the job. *AI Magazine* (51): 95--143.

Forbus, K. (1984) Qualitative Process Theory. *Artificial Intelligence* 24: 85-168.

Jellema, J. 2000. Designing for Support--The Role of Task Knowledge for Designing Support. Masters thesis, University of Amsterdam.

Lenat, D. R., and J. K. Crawford. 1994. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. Hydrobiologica 294: 185-199.

Lemly, D. (1982) Modification of Benthic Insect Communities in Polluted Streams: Combined Effects of Sedimentation and Nutrient Enrichment. *Hydrobiologia* 87: 229-245.

Montgomery, D.R. (2001) *Geomorphology, River Ecology, and Ecosystem Management.* In Geomorphic Processes and Riverine Habitat, Water Science and Application 4: 247-253.

Ohio EPA (1990) *Use of Biocriteria in the Ohio EPA Surface Water Monitoring and Assessment Program.* Ohio Environmental Protection Agency, Division of Water Quality Planning and Assessment, Columbus, Ohio.

Salles, P. and Bredeweg, B. (2003) Qualitative Reasoning about Population and Community Ecology. *AI Magazine* 24(4): 77-90.

Salles, P. and Bredeweg, B. (1997) Building Qualitative Models in Ecology. *Proceedings of the 9th Dutch AI Conference,* NAIC'97, The Netherlands, pgs 181-190.

Sweeney, B.W. (1992) Streamside Forests and the Physical, Chemical, and Tropic Characteristics of Piedmont Streams in Eastern North America. *Water Science Technology* 26: 1-12.

Tullos, D.D., Jennings, G.D., Penrose, D., Shear, T.H., and Shaffer, M.B. Evaluation of Environmental Variables and Governing Concepts in Describing Macroinvertebrates in the Piedmont of North Carolina. Proceedings of the 2004 NABS Annual Meeting, Vancouver, British Columbia.

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