Real-time Monitoring of the Resilience of Stream Ecosystems

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1. Project Summary

This project will develop methods for estimating the *resilience* of a stream's trophic state to variations in nutrient levels and channel flows. These estimates will be obtained from real-time data generated by embedded sensor networks as part of ND-ECI's land use project. The main objectives of this project will be to 1) develop formal models relating a stream's trophic state to environmental variables such as nutrient loading and flow rates, 2) to develop methods for approximating a stream's resilience to perturbations based on real-time sensor data, 3) to validate these methods against existing USGS databases, and 4) to implement these methods for the ND-ECI land use project.

Human-induced pollution is one of the major threats that endanger the availability of fresh water resources and the sustainability of species diversity in aquatic ecosystems. Eutrophication, which describes the excess of nutrient loading that leads to algal blooms and anoxic water, has become a major problem in many aquatic ecosystems [4, 5, 6]. The management of eutrophication is complicated due to the difficulties involved in measuring such a variety of pollutant sources, which range from sewage/industrial discharge to non-point sources such as runoff from agriculture and urban lands. In the United States, eutrophication is driven mainly by the excessive use of fertilizers on agricultural lands, which cause nutrient accumulation in soils and is ultimately transferred to aquatic ecosystems through surface runoff. The negative effects of eutrophication include excessive algal blooms, poor water quality, vegetation shifts and fish kills. Eutrophication has become the most widespread cause of pollution in US aquatic ecosystems, accounting for about half of the damaged lakes and 60% of the impaired streams [1]. These issues indicate the need for immediate action in the management of aquatic ecosystems.

Studies have shown that eutrophication of aquatic ecosystems may cause *regime shifts* among the equilibria of ecosystems [1, 5, 6]. *Regime shifts* often result in catastrophic effects and dramatic changes in the ecosystem's appearance, such as the increase of water turbidity, the loss of species diversity, fish kills, etc. It is well known that these *regime shifts* occur as a consequence of the presence of external perturbations, which forces the ecosystem from one stable state into another. In lakes, regime shifts occur when variations in nutrient loading trigger drastic changes in the *trophic state* and shift its equilibrium. In particular when the amount of nutrient input increases, the lake's equilibrium will move from the low *trophic state* to the unstable equilibrium state. At this threshold point, a sufficiently severe perturbation may shift the system into the high *trophic state* and cause drastic change in the lake's appearance. This shift often happens suddenly, and it is difficult to obtain an early-warning signal for such catastrophic changes. Moreover, when the system's equilibrium has shifted to the high *tropic state*, it is difficult to restore it to its original low *trophic* one due to the presence of new feedback mechanisms that maintain the stability of the new equilibrium. While regime shifts are well documented in lakes, such shifts also occur in other ecosystems. These facts have motivated the need for effective strategies for the management of ecosystems.

The majority of previously proposed management methods have aimed at counteracting *regime shifts* by preventing external perturbations. This approach, however, fails to recognize that a variety of disturbances are in fact natural components that support the biodiversity of ecosystems. A more effective way that has been proposed for managing ecosystems is to maintain the *resilience* of the desired ecosystem state [5, 6]. The notion of *resilience* describes the capacity of a system to remain within a stability domain while subject to external disturbances. Maintaining the *resilience* of system aims to identify the amount of perturbations that can be endured by the system without the loss of its stability regime. In the realm of eutrophication, the goal of *resilience* maintenance is to manage the nutrients entering the stream and stream flow rates to prevent *regime shifts* from occurring [1].

More work is needed to understand the resilience of *streams* to regime shifts. Since streams serve as a primary channel by which agricultural run-off is conveyed to lakes, it is reasonable to believe that managing stream water quality provides an effective tool for preventing regime shifts in downstream receiving waters. It would, therefore, be very valuable to see if notions of resilience, regime shift, and ecosystem management can also be extended to streams. Prior work in streams has studied shifts in channel position as a result of erosion and channelization [3]. Prior work has studied the impact that nutrient levels have on a stream's trophic state [5]. This prior work, however, is not nearly as mature as the work on regime shifts in shallow lakes. This project will develop formal models for understanding the relationship between stream resilience, nutrient loads and stream flows.

With these models, one can develop methods for estimating stream resilience using real-time measurements of the stream's response to environmental perturbations. Most previous studies have focused on *post-hoc* analyses that use historical data to quantify the *resilience* of a system and to predict the possibilities for regime shifts taking place. Unfortunately, such data has usually been collected only on an annual basis. It is thus reasonable to argue that this approach to analysis and this method of data collection fails to capture the transient dynamics of ecosystems. We hypothesize, therefore, in addition to the use of historical data, *real-time* monitoring of nutrient loading and stream flows would provide a more effective way to capture the transient behaviors of the stream and to characterize their *resilience* properties. Statistical estimation methods, moreover, are known to be more accurate if they can take advantage of *a priori* models of the observed process. This project seeks to integrate formal models for regime shifts in streams to develop better algorithms using real-time sensor data to estimate stream resilience.

In summary, this project will develop formal models characterizing the resilience of a stream's trophic state to perturbations in environmental variables such as nutrient levels and stream flow rates. These models will be used with real-time data from embedded sensor networks to develop estimation algorithms for stream resilience.

2. Objectives and Methodologies

The objective of my research is to study the dynamic behaviors of stream ecosystems in response to environmental perturbations. The proposed research is aimed at modeling the impact of variations in nutrient loading, stream flow, and storms and flooding events on water quality and on biodiversity in stream ecosystems. These models will be used to characterize the *resilience* of stream ecosystems and to predict the possibility for *regime shifts* taking place. My research will focus on addressing the following key questions: Which specific measurements are needed in order to model the impact of environmental perturbations on stream ecosystems? How can we use these models and the available high-quality sensor data to characterize the *resilience* of stream ecosystems and to predict the occurrence of *regime shifts*? How can we integrate such measures of *resilience* into land-use management policies?

Methodologies adopted for this research include literature reviews, development of formal models, examination of historical data and field experiments. Literature review will characterize the state-of-the-art in stream ecosystem modeling as it pertains to *resilience* analysis. Formal modeling efforts will seek to capture the underlying mathematical relationships between stream trophic state and environmental variables such as nutrient load and stream flows. Methods for nonlinear dynamical systems theory will be a central tool for these purposes. These models will be used to develop methods for estimating stream resilience to these environmental factors and historical databases will be used to help validate these methods. This project will also make use of the ND-ECI land use project's sensor network to see how best to use estimates of stream resilience in land-use management protocols. The data collection process associated with ND-ECI's land-use project will take advantage of wireless sensor network technologies developed by an industrial partner, EmNET LLC. These technologies allow us to remotely measure in real-time the amount of nitrogen loads and other relevant data related to stream health. Since EmNET data will be held in MySQL database, my work will involve developing computational tools to retrieve data that are relevant for real-time monitoring of stream's dynamics.

3. Relevance of the proposed research to the current ND-ECI research project

The proposed research is strongly relevant to the *ND-ECI Land Use* project. The land use project seeks mechanisms for managing agricultural land use practices to balance farm productivity against excessive nutrient loading of lakes and streams. The monitoring technologies and dynamic models developed in this project will provide real-time measurement on the amount of nutrient loading and its impact on the health of stream ecosystems. By measuring in real-time the sensitivity of a stream's trophic state to environmental perturbations, we obtain a way of assessing how close an ecosystem might be to collapse [2]. These measures of resilience may be extremely useful in developing realistic valuations of the stream ecosystem. These valuations could then be used in developing cap-and-trade policies that encourage farmers to adopt practices that more fairly balance a farm's profitability against the cost associated with catastrophic shifts in the stream's ecosystem. In this regard, a better understanding of a stream's resilience to perturbations in nutrient levels and channel flows will be an important part of ND-ECI's land use project.

4. Plan for the dissemination of research findings

Dissemination of findings from this research will primarily be done through peer-reviewed publication. The research partnership with EmNET LLC will provide a means for practical implementation of the obtained theoretical results. Research findings can also provide information for The Nature Conservancy to improve the practical management of stream ecosystems or can be used by the USDA or local government to guide agricultural land use policies.

References

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