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Using Eutrophication Modeling to Predict the Effectiveness of River Restoration Efforts

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Abstract

Massive summer fish kills in 1995 drew public attention to the deteriorating water quality in North Carolina's Neuse River Estuary. Nitrogen loading to the estuary has increased dramatically due to increases in population, agricultural activity, and livestock production. Widespread anoxia and fish kills have occurred occasionally in the Neuse River Estuary in the past, but occurred in both 1995 and 1996. In addition, problems associated with algal blooms and macrophytes are at all time highs. In response, the State has drafted regulations aimed at reducing nitrogen loading to the estuary by 30 percent. At the same time, the State has funded a research project to predict the water quality improvement that will result from reduced nutrient loading, and to plan for future management of the river basin. This three-phase project, referred to as MODMON (MODeling and MONitoring), will include collection of tightly coupled water quality, fisheries, hydrodynamic, and sediment data; application of a eutrophication model to predict the results of reduced nitrogen loading; and development of recommendations for longer-term development of a watershed-river-estuary water quality model focusing on management outcomes. Results from initial water quality monitoring showed the estuary to be intermittently anoxic even during "good" years such as 1997. The special characteristics of the predictive eutrophication modeling effort now underway are also discussed. These characteristics include a large database of water quality and ecosystem rate measurements, the existence of a multi-disciplinary monitoring effort, parallel short-term and long-term model development efforts, and incorporation of an uncertainty analysis into the process-based eutrophication model.

Introduction

North Carolina's Neuse River drains approximately 16,000 km^2, and empties into the southwestern corner of the Pamlico Sound. The Raleigh-Durham metropolitan area is within the basin, near the river's headwaters. Nearly 1.5 million people live in the

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river basin. The basin is also used intensively for agricultural and livestock production. The estuary occupies the lower 80 km of the river. It is broad and shallow, with average depths ranging from approximately 4 m near New Bern to 6 m at the mouth. The upper reach of the estuary, near New Bern, is oligohaline, while the lower estuary, from upstream of Cherry Point to the Pamlico Sound junction is mesohaline (Giese et al 1985).

The upper estuary is considered eutrophic and has experienced numerous blooms of blue-green algae (Hobbie and Smith 1975, Paerl 1987). The lower estuary is considered mesotrophic, and has recently experienced dinoflagellate blooms (Rudek et al. 1991, Mallin and Paerl 1994). Unfortunately water quality conditions have deteriorated significantly in the last few years. Periods with low dissolved oxygen (DO) concentrations and fish kills have occurred in the past, but were widespread and serious in both 1995 and 1996. In 1995, heavy summer rains followed by a prolonged period of density stratification lead to summer algal blooms, widespread anoxia (defined here as DO concentration < 2 mg/l), and massive fish kills (Paerl and Pinckney 1996). An outbreak of the toxic algae *Pfiesteria piscicida* (Burkholder et al 1995) also occurred, and was considered to be the cause of many of the fish deaths. A similar scenario occurred in 1996, after the passage of Hurricane Fran. Anoxia and fish kills occurred along the entire estuary. While problems associated with excessive nutrient loading, algal blooms, anoxia, macrophyte mortality, and fish kills have been documented for over twenty years, all of these water quality problems are presently at all time highs.

Neuse River MODeling and MONitoring (MODMON)

In response to these water quality problems, the State has designated the Neuse River a "nutrient sensitive water," and has drafted a management strategy with the goal of reducing nitrogen loading by 30 percent. The state has also funded a water quality modeling and monitoring project (referred to as MODMON) that is being conducted by an interdisciplinary team of scientists from North Carolina universities. This project consists of three parallel efforts, with the following objectives:

- design and begin implementation of a monitoring program that will provide a tightly coupled water quality, fisheries, hydrodynamics, and sediment data set suitable for use in a water quality model application and for guiding long-term modeling work;

- develop and calibrate a two-dimensional, laterally-averaged eutrophication model; then apply and test the model to predict the result of the proposed management actions (including the 30% reduction in total nitrogen loading), determine which gaps in scientific knowledge are most important, and estimate the reliability of model predictions;

- produce guidance for developing a long-term watershed-river-estuary water quality model that focuses on management outcomes by explicitly linking proposed management actions (e.g. forested buffers) in the watershed with publicly meaningful estuarine responses (e.g. fish kills).

In this article we discuss some of the early results and special features of this research.

Early Results

1997 was considered a relatively good year in terms of water quality and fish kills in the Neuse River Estuary. Nonetheless, results from the MODMON water quality monitoring program indicate that bottom water DO concentrations in the estuary were frequently below 2 mg/l (Figure 1) during 1997. Weekly surveys were conducted during the summer, where vertical profiles of DO concentration were collected from 17 mid-channel stations. The region near New Bern (approx. 14 km downstream from the head of the estuary) was most frequently anoxic (DO < 2 mg/l) in the bottom water, and this region was anoxic during every survey from early July through the end of August. The remainder of the estuary was intermittently anoxic, with anoxia being most widespread from mid-June through mid-August. On several occasions, the bottom water anoxia was present even at the estuary mouth, which is far removed from the primary nutrient source upstream. Significant differences were seen in the extent of bottom water anoxia from

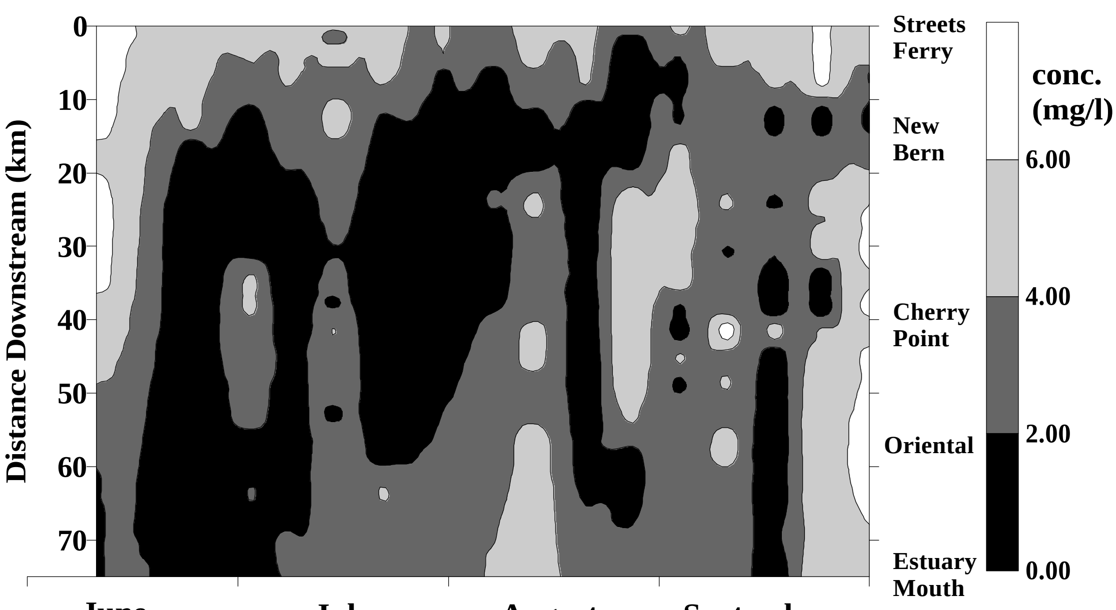

Figure 1. Neuse River Estuary Bottom Water DO Concentrations during Summer 1997

week-to-week. In addition, in any given week, significant spatial differences were seen in the bottom water DO concentrations (Figure 1). Water quality conditions began to improve in August, although "pockets" of bottom water anoxia were observed in every survey through the end of September.

Special Features of the Eutrophication Modeling

The use of a eutrophication model to predict the impact of changing nutrient loadings is not at all unusual, as many such studies have been performed previously (e.g. Cerco and Cole 1993, Hydroqual and Normandeau 1995). There are, however, special features of this effort, which when taken together, seem unique. The first of these is the large database of previously collected information on water quality and ecosystem rate processes in the estuary. Research on nutrient dynamics in the water column and sediments of the Neuse River Estuary have been ongoing for over twenty years. During the last decade, there have been studies of nutrient distributions within the estuary (Christian et al. 1991), on the local and ecosystem level factors regulating primary production (Rudek et al.1991, Boyer et al. 1993), on the significance of nutrient and oxygen exchange with the sediments (Rizzo and Christian 1996), on zooplankton grazing rates (Mallin and Paerl 1994), and on hydrodynamics and conservative material transport within the estuary (Robbins and Bales 1995). Rarely is such a wealth of information available.

A second special characteristic of the MODMON project is the coupling of the modeling to a comprehensive multi-disciplinary monitoring project. During project planning it was determined that the previous data collection, although extensive, had neither the spatial coverage, nor all the parameters necessary for a coupled circulation/eutrophication model. To remedy this, beginning in June 1997, the eutrophication modeling is being supported by water-column and sediment monitoring. While modeling studies usually include companion monitoring work, the MODMON project is special in that the monitoring work is comprehensive, including hydrodynamic, water quality, benthic chemistry and biology, sediment flux, and fisheries monitoring. In addition, water quality profiles are being collected along transects oriented both along and across the river channel to investigate the implications of using laterally-averaged hydrodynamic and eutrophication models. This monitoring is done not only to complement the current modeling effort, but also to better understand system dynamics, and to guide future model development work.

The MODMON project is also unusual in that it includes parallel modeling efforts. By early 1999, the eutrophication modeling work described here will produce a prediction of the impact on water quality of reducing nitrogen loading to the Neuse River Estuary by 30 percent. This modeling will focus on using process-based hydrodynamic and eutrophication models to predict how chlorophyll-a and dissolved oxygen concentrations will be affected by reduced nutrient loadings. Impacts to fisheries, or macrophytes, or on toxic algae such as *Pfiesteria* will not be predicted directly. Recognizing this, the MODMON project includes a parallel effort at long-term model development. This "long-term" model will likely be a coupled watershed-river-estuary model, and will probably include components that are probabilistic, rather than process based. The model system will be intended for use by environmental managers as a tool for managing the resource.

Finally, the eutrophication modeling is special in the emphasis that is being placed on estimating the uncertainty of all predictions. The motivation for estimating uncertainty stems from the model's use in guiding decision making about water quality management.

The modeling will be based on application of a laterally-averaged, process-based eutrophication model (Cole and Buchak 1995), applied in a way so that each model prediction includes a clear statement regarding the reliability of the prediction. Prediction uncertainty stems not only from errors arising from discretization, the use of simplifying assumptions, and errors in measurements of forcing functions, but also from uncertain parameter specification. Prediction error will be assessed during calibration and will be combined with an estimate of parameter uncertainty using the method of Brooks et al. (1994) modified for use in eutrophication modeling. An analysis of this sort has been performed recently (Bowen 1997), and has proven to be a useful procedure for estimating the uncertainty of estuarine water quality predictions.

Discussion and Conclusions

The modeling effort now underway in many ways resembles the previous efforts in the Chesapeake Bay. In both systems the objective of environmental regulation is to reduce nutrient loading to the estuary. A process-based eutrophication model is the mechanism used to predict water quality conditions under various nutrient loading scenarios. The negative impacts of eutrophication are also very similar in the two systems, including algal blooms, loss of benthic habitat for commercial shellfish and other macroinvertebrates, oxygen depletion, die-off of sea grass beds, and blooms of the toxic algae *Pfiesteria*. It is expected, therefore, that the future development of the Neuse River model system will add watershed and riverine fate and transport models, as the Chesapeake modeling effort has done.

As described earlier, the eutrophication modeling for the Neuse River has several special characteristics. It will also face several unusual challenges, which are related both to the intended use of the model results and to the system being modeled. The results of the model will be intensely scrutinized by groups representing the interests of environmentalists, municipalities, farmers, and hog farm operators (these groups are not assumed to be mutually exclusive). This will place special emphasis on the clear and careful presentation of model results, which are often complicated and highly technical. In addition, the system itself poses special challenges. The system is dynamic and spatially heterogeneous. Different groups of algae bloom in the oligohaline and mesohaline portions of the estuary. Water quality conditions are dependent on the delicate interplay between riverine input, vertical mixing, flushing, and benthic processes. The capabilities of the current state-of-the-art in eutrophication modeling will be severely tested in this application.

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