NUTRIENT CRITERIA DEVELOPMENT WITH A LINKED MODELING SYSTEM: CALIBRATION OF AQUATOX ACROSS A NUTRIENT GRADIENT

Richard A. Park, Ph D, Eco Modeling, Diamondhead, MS 39525
Jonathan S. Clough, Warren Pinnacle Consulting, Inc., Warren, VT 05674
Marjorie C. Wellman, U.S EPA, Office of Science and Technology, Washington, D.C. 20460
Anthony S. Donigian, Jr., P.E., AQUA TERRA Consultants, Mountain View, CA 94043

Eco Modeling
5522 Alakoko Place
Diamondhead MS 39525

ABSTRACT

Nutrients (nitrogen and phosphorus) are leading causes of water quality impairment in the Nation's rivers, lakes and estuaries. To address this problem, states need the technical resources to establish nutrient criteria, adopt them into their water quality standards, and implement them in regulatory programs. In recent years EPA developed and finalized a series of nutrient criteria documents to assist the states in adopting nutrient standards. Unlike most water quality criteria, the nutrient criteria were not based on finding cause and effect relations between pollutant levels and adverse water conditions. Rather, the criteria were based on assessing natural background and cultural eutrophication in 14 ecoregions in the country. However, as specified in the documents, states and tribes have the option of developing nutrient criteria using other scientifically defensible methods and data.

This paper discusses one aspect of a demonstration project that uses the watershed model HSPF and the aquatic ecosystem model AQUATOX, which are both part of EPA's BASINS package. AQUATOX is used to link aquatic nutrient concentrations with concentrations of "response variables" (chlorophyll-a, algal composition, water clarity), and HSPF is used in turn to link land use practices with nutrient concentrations. The demonstration project, developed in partnership between EPA and the Minnesota Pollution Control Agency (MPCA), is the first of what may be several geographically diverse projects developed to illustrate the utility of models for developing nutrient criteria in different parts of the country. This paper reports on calibration of AQUATOX across a nutrient gradient in order to develop an ecoregional implementation of the model. By developing a robust parameter set for organisms that are adapted to either nutrient-rich or nutrient-poor conditions, the model is more likely to represent changing conditions and to not require extensive site calibration in future applications.

AQUATOX can model periphyton, phytoplankton, macrophytes, invertebrates, and fish as well as nutrients, sediments, and pesticides. It has been used to simulate high-nutrient rivers; however, it had not been previously calibrated for low-nutrient riverine conditions. This project was intended to represent the development of criteria and assessment of use attainability for the nutrient-rich, turbid Blue Earth River and the nutrient-poor, clear Crow Wing River. In a companion paper AQUATOX was used to predict the response to various permit and land-use changes that could affect nutrients, total suspended solids, and herbicides.

Application of the model to the Crow Wing River site required the addition of algal species that are adapted to low-nutrient conditions. The high-nutrient species were calibrated so they would be at a competitive disadvantage and would decline in the simulation. Likewise, the low-nutrient species were added to the Blue Earth River simulation and were calibrated so they would be at a competitive disadvantage in that system. By this means we developed a parameter set for organisms that can represent the full range of nutrient conditions, with replacement or succession as conditions change. The model was then tested and calibrated further with data from the Rum River, which has intermediate nutrient conditions and low TSS. Thus our comfort level was increased in representing changing conditions in both the Blue Earth and Crow Wing Rivers.

Separate companion papers present the overall project methodology and demonstration study results; and the watershed model development and application efforts, with the model results and linkage procedures to AQUATOX comprising the framework of the assessment methodology.

KEYWORDS

Nutrients, nutrient criteria, nutrient ecoregions, AQUATOX, HSPF, ecosystem modeling.

INTRODUCTION

Overview

In a project developed in partnership between the U.S. Environmental Protection Agency (US EPA) and the Minnesota Pollution Control Agency (MPCA) and involving AQUA TERRA Consultants, Eco Modeling, and Warren Pinnacle Consulting as contractors, the utility of the HSPF watershed model (Bicknell *et al.*, 2001, Duda *et al.*, 2002) and the AQUATOX aquatic ecosystem model (Park and Clough, 2004) in developing nutrient criteria was demonstrated. The approach exemplified the use of historical data, predictive models, expert judgment, and consideration of potential downstream effects. A companion paper (Donigian *et al.*, 2005) describes in detail the rationale behind the approach, the application of the HSPF, and the linkage to the AQUATOX model. Another companion paper (Carleton *et al.*, 2005) describes the determination of the nutrient criteria and application of the management strategies.

A project by the MPCA with US EPA funding found significant and predictable relationships among nutrients, total suspended solids (TSS), biological oxygen demand (BOD), and algae in five medium to large rivers (Heiskary and Markus, 2003). The data collected by the MPCA and USGS were used in calibration of the HSPF and AQUATOX models for this project. Ancillary data on pesticides from the Minnesota Department of Agriculture also were used in the AQUATOX application.

AQUATOX Model

The AQUATOX model is a general ecological risk assessment model that represents the combined environmental fate and effects of conventional pollutants, such as nutrients and sediments, and toxic chemicals in aquatic ecosystems. It considers several trophic levels, including attached and planktonic algae and submerged aquatic vegetation, invertebrates, and forage, bottom-feeding, and game fish; it also represents associated organic toxicants. The model was first developed in 1987 and has been continually expanded and enhanced since then (Park *et al.*, 1988, Park, 1990, Park *et al.*, 1995, U.S. Environmental Protection Agency, 2000, U.S. Environmental Protection Agency, 2001, Park and Clough, 2004).

Site Descriptions

The Blue Earth River watershed is located in the Western Corn Belt Plains, part of the Aggregate Nutrient Ecoregion 6 (Figure 1, see also Donigian et al. 2005). The upper Crow Wing River watershed is located in the Northern Lakes and Forests, part of the Aggregate Nutrient Ecoregion 8. The Rum River watershed is located in the North Central Hardwood Forests.

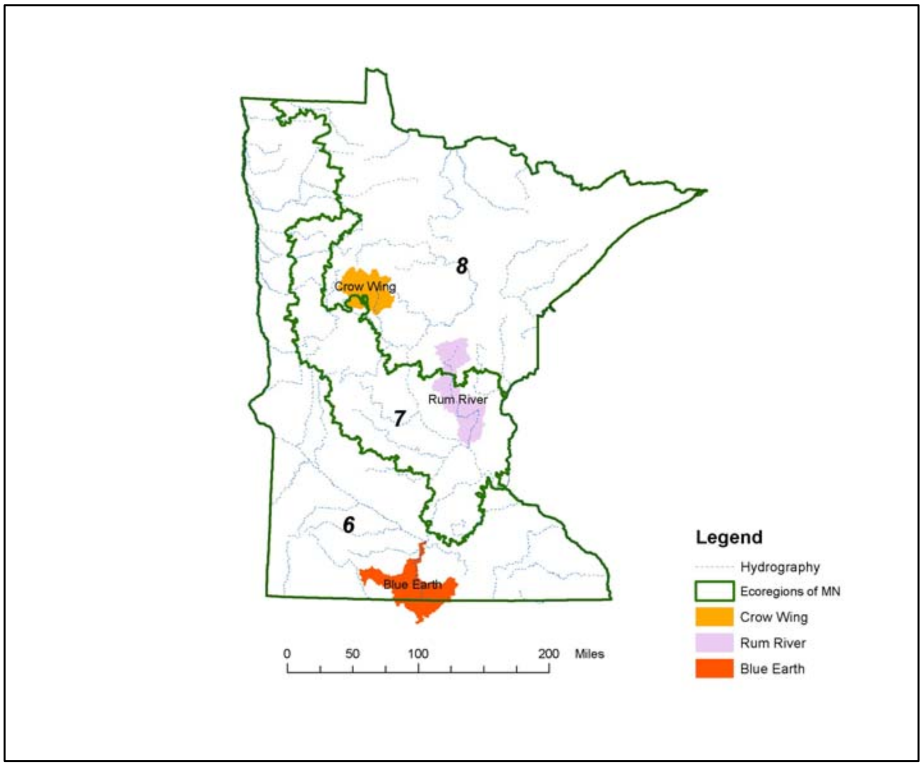


Figure 1. MPCA River Nutrient Study Sites.

All three rivers are shallow (for example, Figure 2) and are capable of supporting diverse periphyton communities, which vary in composition according to their position on a nutrient gradient (Figure 3). The Crow Wing River has relatively low levels of nutrients and low turbidity. The Rum River has moderate levels of nutrients and low turbidity. The Blue Earth River has high levels of nutrients and periodically high turbidity.

Figure 2. Rum River, Minnesota (Heiskary and Markus, 2003).

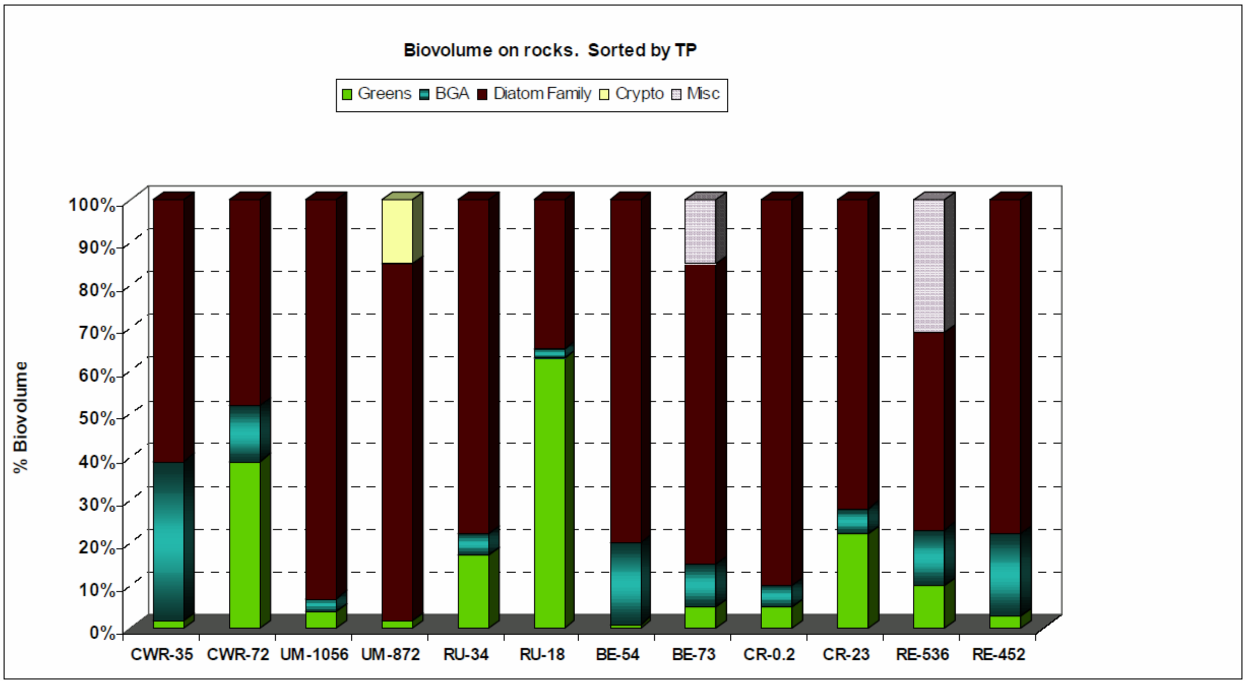


Figure 3. Periphyton percent biovolume on rock. Sites sorted based on summer-mean TP for 2000 (Heiskary and Markus, 2003). CWR: Crow Wing, UM: Upper Mississippi, RU: Rum, BE: Blue Earth, CR: Crow, RE: Red.

Likewise, the phytoplankton composition varies from one river to another in a systematic fashion (Figures 4, 5, 6).

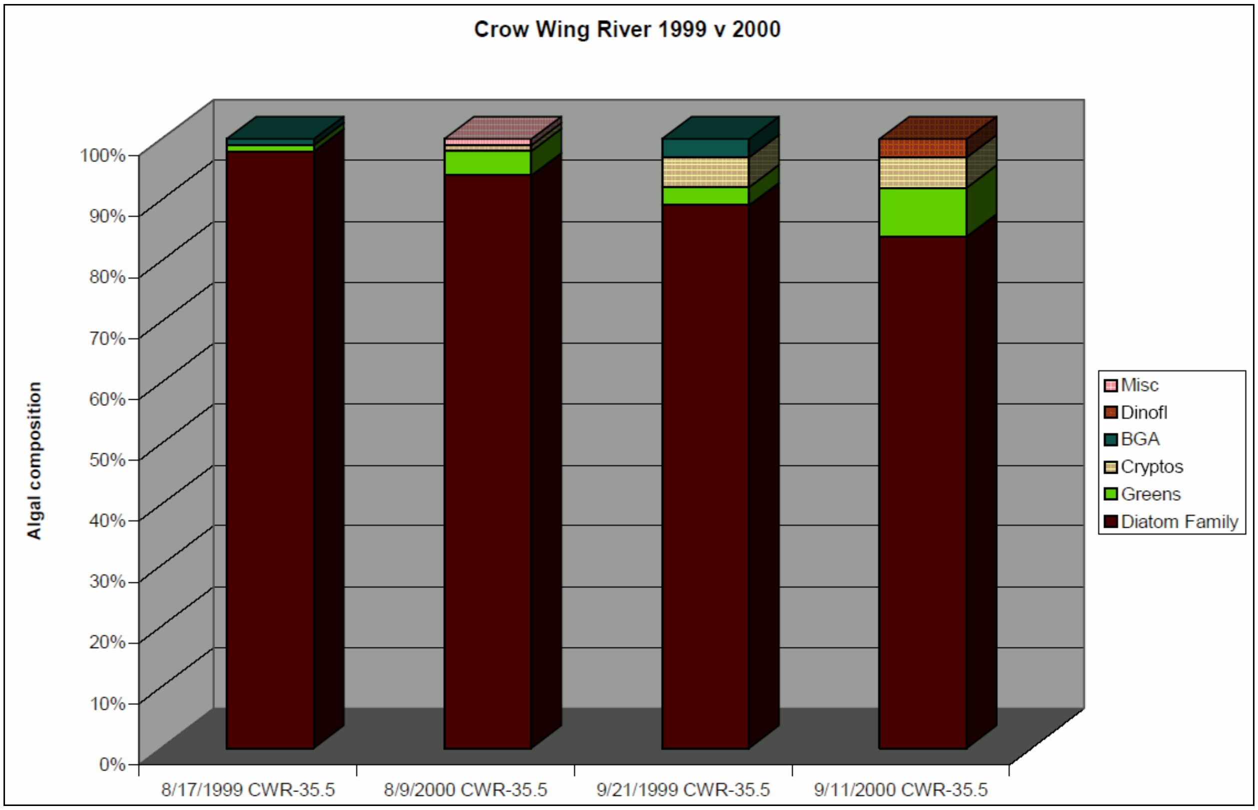


Figure 4. Phytoplankton composition in the Crow Wing River (Heiskary and Markus, 2003).

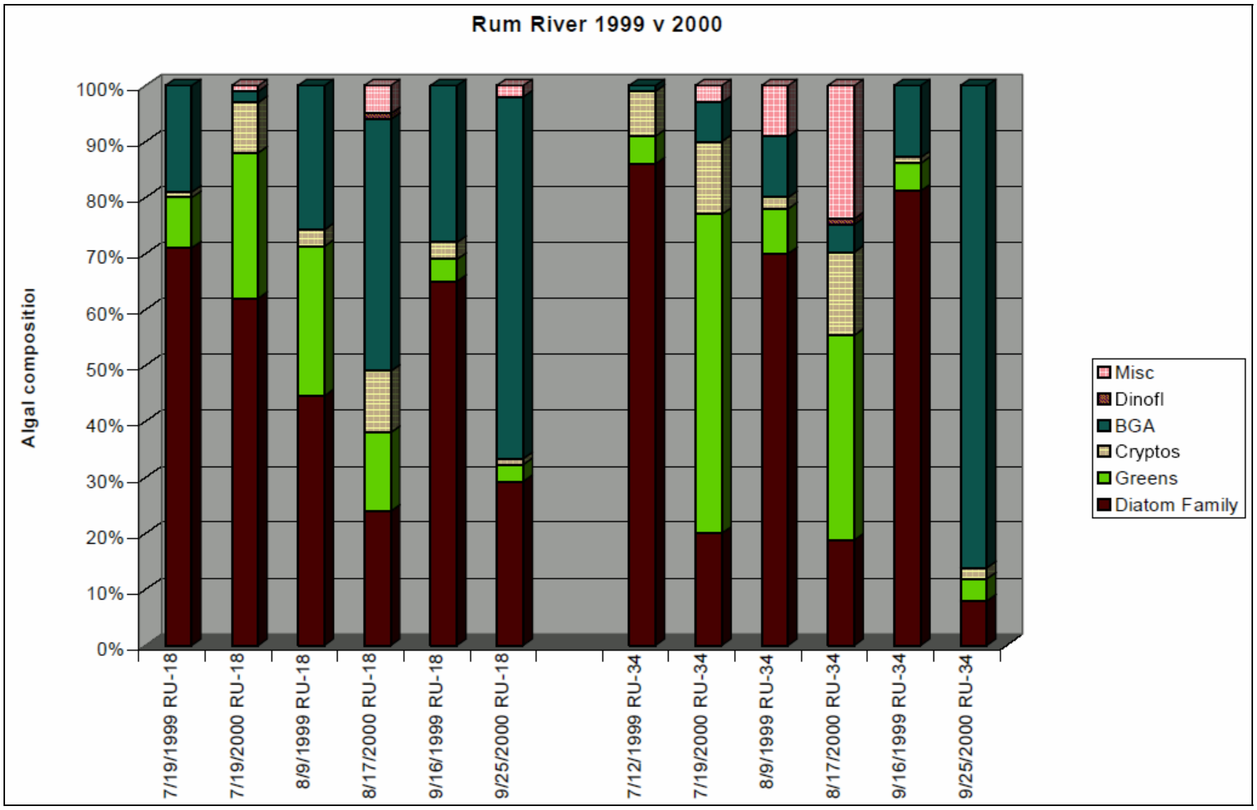


Figure 5. Phytoplankton composition in the Rum River (Heiskary and Markus, 2003).

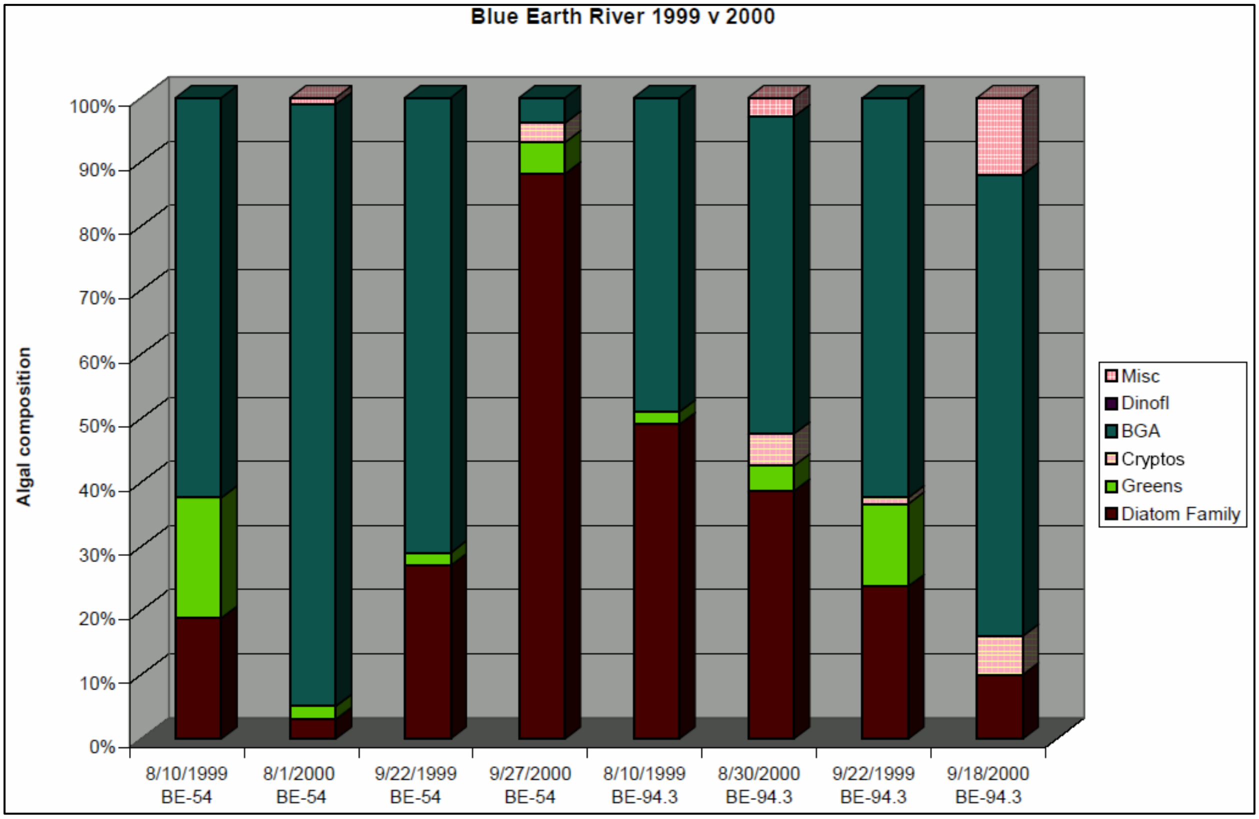


Figure 6. Phytoplankton composition in the Blue Earth River (Heiskary and Markus, 2003).

CALIBRATION

State Variables

State variables were chosen to represent both the nutrient-poor, clear-water Crow Wing River and the nutrient-enriched, turbid Blue Earth River. Sculpin, a cold-water fish, was included although conditions in the Blue Earth River are too warm for its continued survival. Because the objective was to obtain a set of state variables that would span the conditions on the Minnesota rivers, the number of state variables (Fig. 7) is larger than if a single river with static conditions were being simulated. In fact, the number of algal groups is almost double that required if the model were calibrated for present conditions in a single river.

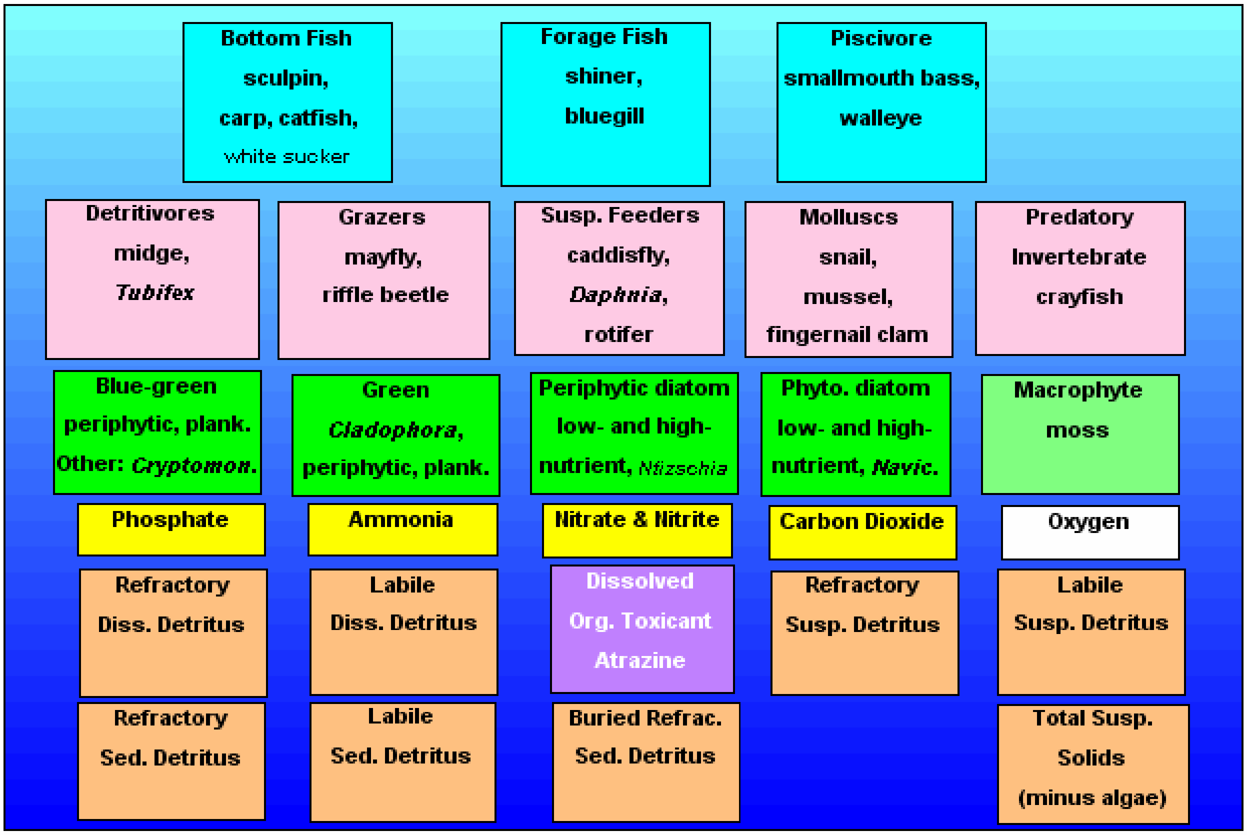


Figure 7. State variables in Minnesota rivers simulations.

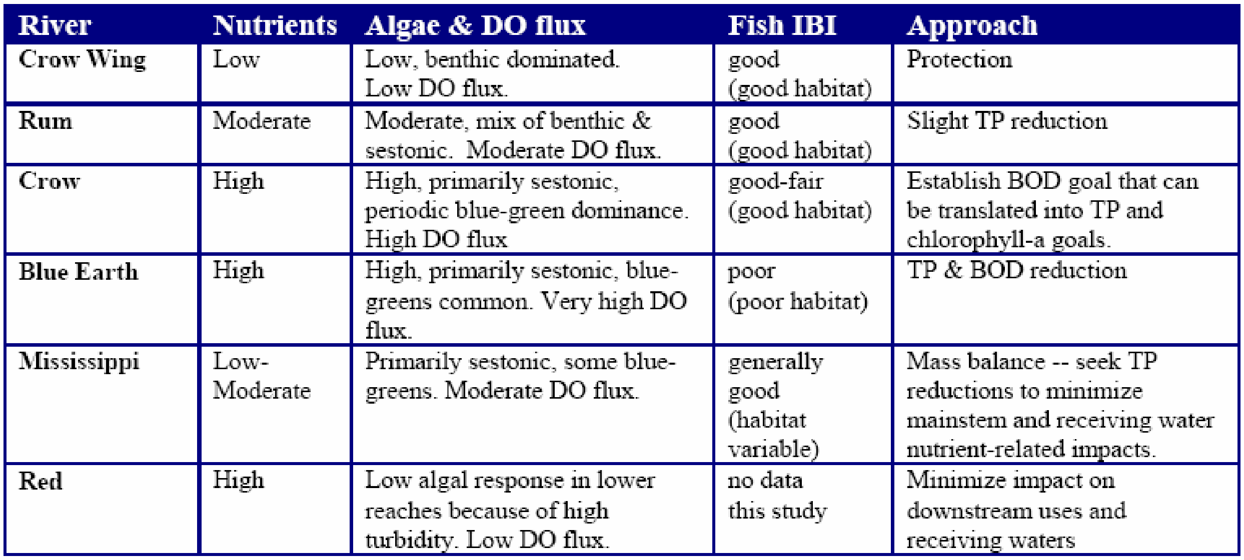
Calibration Parameters

In almost all cases parameter values were chosen from ranges reported in the literature (for example, Le Cren and Lowe-McConnell, 1980, Collins and Wlosinski, 1983, Jorgensen *et al.*, 2000, Wetzel, 2001, and Horne and Goldman, 1994). However, because these often are broad ranges and the model is very sensitive to some parameters, iterative calibration was necessary for a subset of parameters in AQUATOX. Conversely, many parameters have well established values and default values were used with confidence. A few parameters such as extinction coefficients and critical force for sloughing of periphyton are poorly defined or are unique to the AQUATOX formulations and were treated as “free” parameters subject to broad calibration. For example, some periphyton species are able to migrate vertically through the periphyton mat, and other have open growth forms; therefore, they could be assigned extinction coefficient values without regard to the physics of light transmission through biomass fixed in space.

Target Variables

Nutrient criteria are based on a variety of response variables (Table 1). Water-column chlorophyll *a* and dissolved oxygen are used traditionally, perhaps because they are easy to measure. Periphytic chlorophyll *a* is being used increasingly in streams. Algal composition is important if it involves taste- and odor-producing and potentially toxic forms such as blue-greens (cyanobacteria). Invertebrate and fish compositions often are used to calculate biotic indices.

Table 1. Approaches for setting nutrient criteria in Minnesota (Heiskary and Markus, 2003).



River	Nutrients	Algae & DO flux	Fish IBI	Approach
Crow Wing	Low	Low, benthic dominated. Low DO flux.	good (good habitat)	Protection
Rum	Moderate	Moderate, mix of benthic & sestonic. Moderate DO flux.	good (good habitat)	Slight TP reduction
Crow	High	High, primarily sestonic, periodic blue-green dominance. High DO flux	good-fair (good habitat)	Establish BOD goal that can be translated into TP and chlorophyll-a goals.
Blue Earth	High	High, primarily sestonic, blue-greens common. Very high DO flux.	poor (poor habitat)	TP & BOD reduction
Mississippi	Low-Moderate	Primarily sestonic, some blue-greens. Moderate DO flux.	generally good (habitat variable)	Mass balance -- seek TP reductions to minimize mainstem and receiving water nutrient-related impacts.
Red	High	Low algal response in lower reaches because of high turbidity. Low DO flux.	no data this study	Minimize impact on downstream uses and receiving waters

Calibration of AQUATOX for the Minnesota rivers used the algal variables, chlorophyll *a* and composition, as targets for obtaining best fits. Because there were few data points, suitable calibrations were based on reasonable behavior and appropriate concordance with observed values as determined by graphical comparisons. Dissolved oxygen is not a problem in the rivers studied (DO flux is a measure of productivity). The predicted invertebrate and fish biomasses were inspected for reasonable values, and adjustments were made as deemed necessary.

Possible Effects of Herbicides

The Blue Earth River basin is largely planted in row crops, and pesticides are used extensively. There was concern that herbicides might affect the algae, biasing the nutrient response. AQUATOX was run with observed levels of the prevalent herbicide atrazine added to the initial calibrated model. No effects were observed, suggesting that herbicides could be ignored.

Iterative Approach

Initially, rather than linking to HSPF, the model was run with observed discharge and nutrient data for both the Blue Earth and Crow Wing Rivers to obtain preliminary calibrations. Sensitivity analysis showed that TSS are important in the Blue Earth River. Because of the sensitivity, daily TSS values were needed to drive the model. These were obtained by regressing observed TSS against discharge, yielding an acceptable fit (Fig. 8). The Crow Wing River, which has few fine-grained sediments, showed no relationship between TSS and discharge so a constant TSS value was used.

The stand-alone implementation of AQUATOX for the Blue Earth River had several problems:

- discharge at downstream gage had to be scaled back to obtain an estimated discharge
- TSS vs. discharge is a tenuous relationship
- sparse data are available for nutrients and BOD and large interpolations are required
- mean depth can be critical and may not be modeled as well as with a hydrologic model.

Of these, the most serious was that the only USGS gaging station in the study area is 42 miles downstream from the study site.

These problems are less severe in the Crow Wing River implementation because the study site is located next to the USGS gage; however, large interpolations are still required for nutrient and organic loadings, and there are uncertainties in the simulated mean depth. For these reasons the stand-alone calibrations were quickly supplanted by simulations based on linkages to HSPF.

First the model was calibrated against observed data for the Blue Earth River, then the same parameter set was used to simulate the Crow Wing River. Adjustments were made to parameters, especially for the low-nutrient algae, until a suitable fit was obtained, and then the new values were used to simulate the Blue Earth River, and further adjustments were made. This iterative approach proceeded until both sites were suitably represented by the same parameter set.

The next step was to attempt to validate the two-site calibration with data from the Rum River. HSPF was not run for the Rum River basin; a stand-alone implementation was used with the same parameter set. However, the fit was not satisfactory. A combination of moderate nutrients and low turbidity seems to favor green algae in ways not predicted by the experience with the low- and high-nutrient sites, and additional calibration was indicated. So, rather than using the site for validation, the decision was made to calibrate across all three sites.

Simultaneous Calibration

To avoid reentering parameter values between sites and to speed up the calibration, a modification was made to AQUATOX Release 3, which is in alpha test now. Release 3 represents linked segments sharing a common parameter set. The model was made more general so that separate, unlinked sites could be simulated simultaneously with a common parameter set. Thus, the effect of a change in a parameter value could be evaluated across all three sites and changed accordingly. A one-year simulation for the three riverine sites takes about 45 minutes on a Pentium 4 2.8 GHz machine. The procedure is not only efficient, it facilitates comparisons among the three sites.

Construct Modification

During the course of simulating the Minnesota rivers it became evident that some changes to the code were necessary. These will be mentioned without going into details. The most important change was to represent the “residence time” of phytoplankton in the river. Phytoplankton not only wash downstream, they also wash in from upstream. Prior to this study, riverine phytoplankton were virtually ignored in AQUATOX implementations. However, observations in the Blue Earth River in particular indicated that phytoplankton blooms are important at times, so the model was modified to represent the potential for phytoplankton and zooplankton growth upstream from the reach under consideration. A second modification was to fine-tune the construct for periphyton sloughing, calibrating the sensitivity of sloughing to environmental factors that stress the algae. A third minor modification was to model phytoplanktonic blue-greens as floating in the top 0.1 m rather the top 0.3 m of water. Finally, periphyton and phytoplankton compartments were linked so that sloughing periphyton is added to a phytoplankton compartment for Chlorophyll a accounting, and so that a fraction of settling phytoplankton is added to active periphyton beds.

RESULTS

Simultaneous calibration across the three sites resulted in good fits to widely varying chlorophyll *a* levels and acceptable fits to compositional patterns. Crow Wing River phytoplankton are dominated by low-nutrient diatoms (Figure 8). Two predicted blooms are not supported by the data (Figure 9), but represent transient sloughing events from the periphyton.

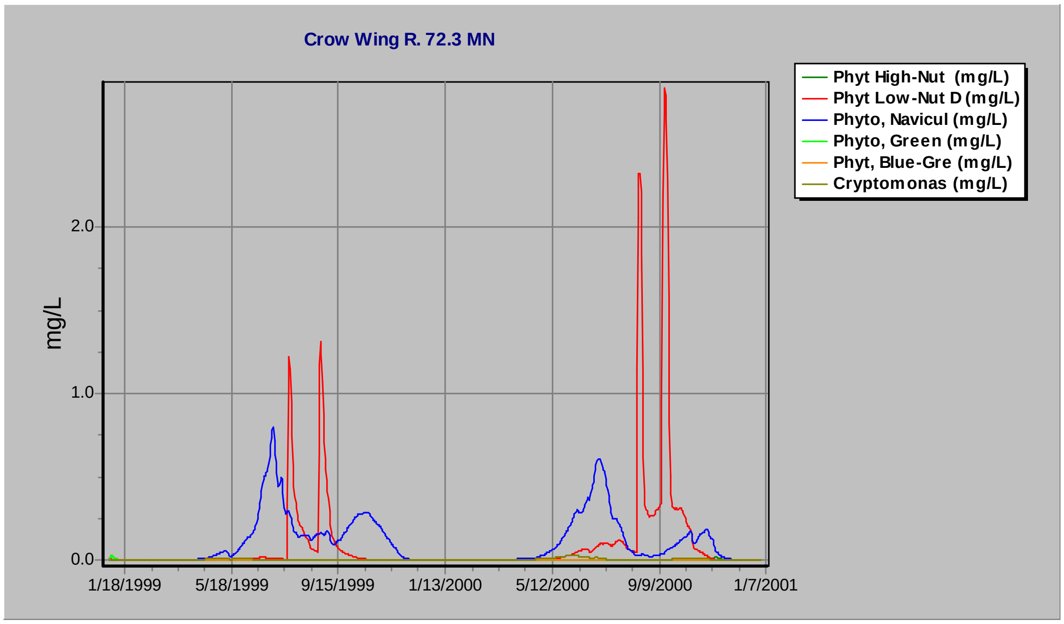


Figure 8. Predicted phytoplankton composition in Crow Wing River.

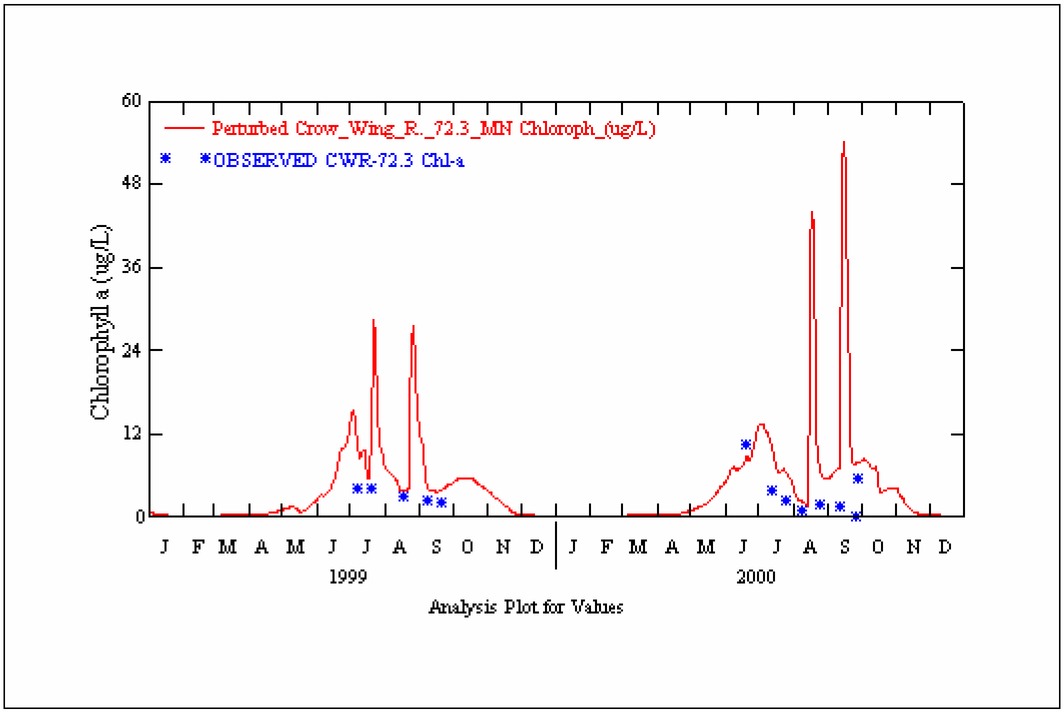


Figure 9. Predicted and observed phytoplankton chlorophyll a in Crow Wing River.

The Crow Wing periphyton are diverse, but are dominated by low-nutrient diatoms and green algae (Figure 10) similar to what was observed (Figure 3). As with all periphyton samples, there is only one observation for comparison, but the fit is acceptable (Figure 11).

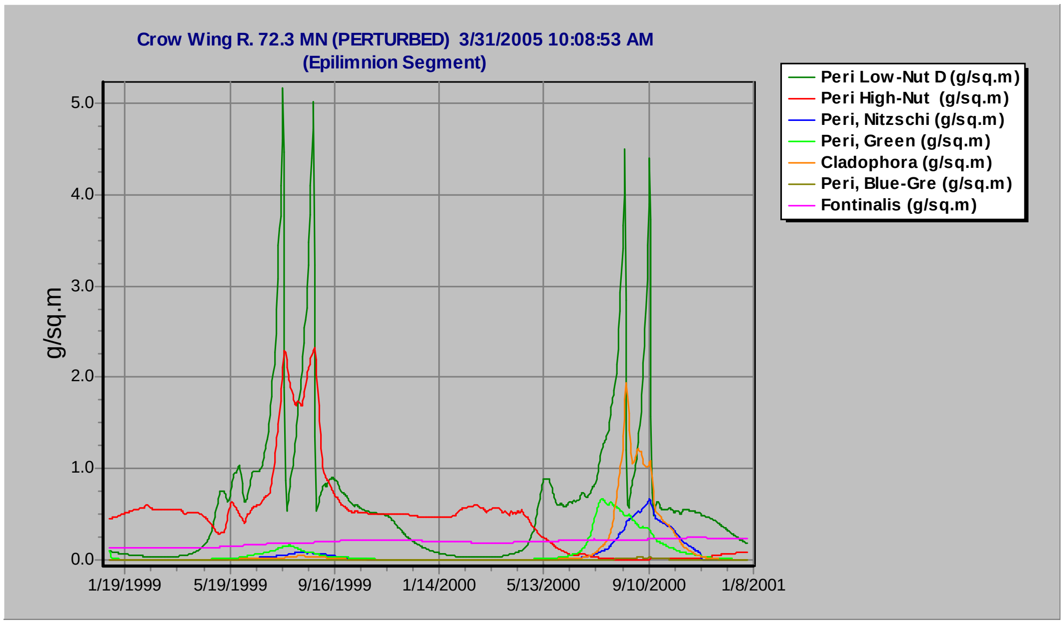


Figure 10. Predicted periphyton composition in Crow Wing River.

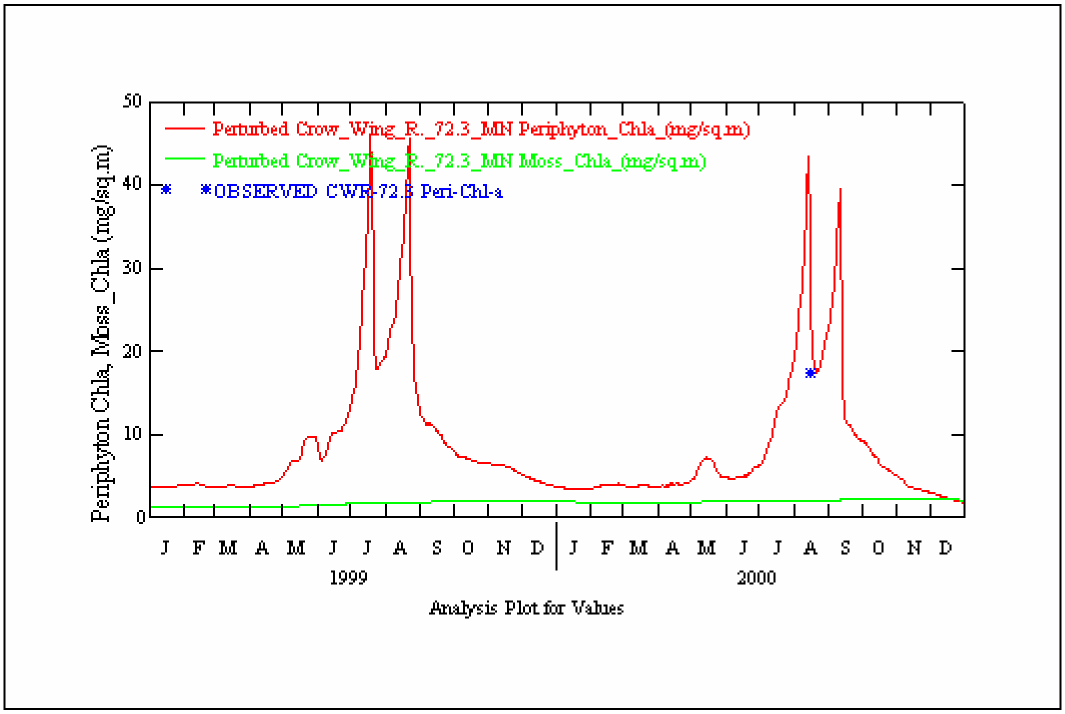


Figure 11. Predicted and observed periphyton chlorophyll a in Crow Wing River.

The predicted Rum River phytoplankton are dominated by high-nutrient diatoms in a series of blooms (Figure 12); the blue-greens that are also important in the observed data (Figure 5) are not well represented in the simulation. The predicted biomass levels compare favorably with the observations (Figure 13).

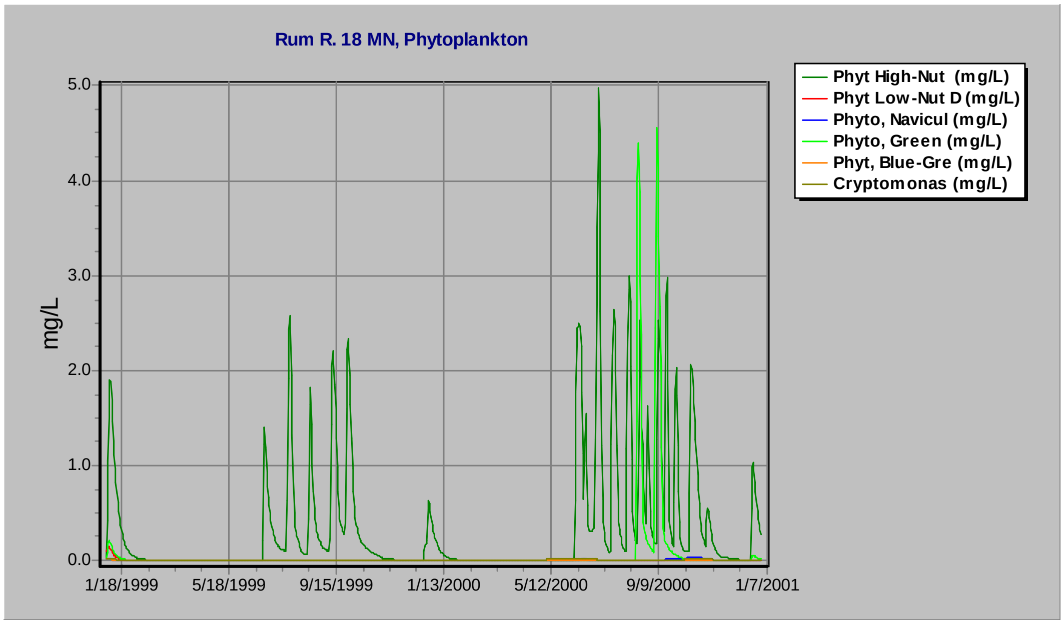


Figure 12. Predicted phytoplankton composition in Rum River.

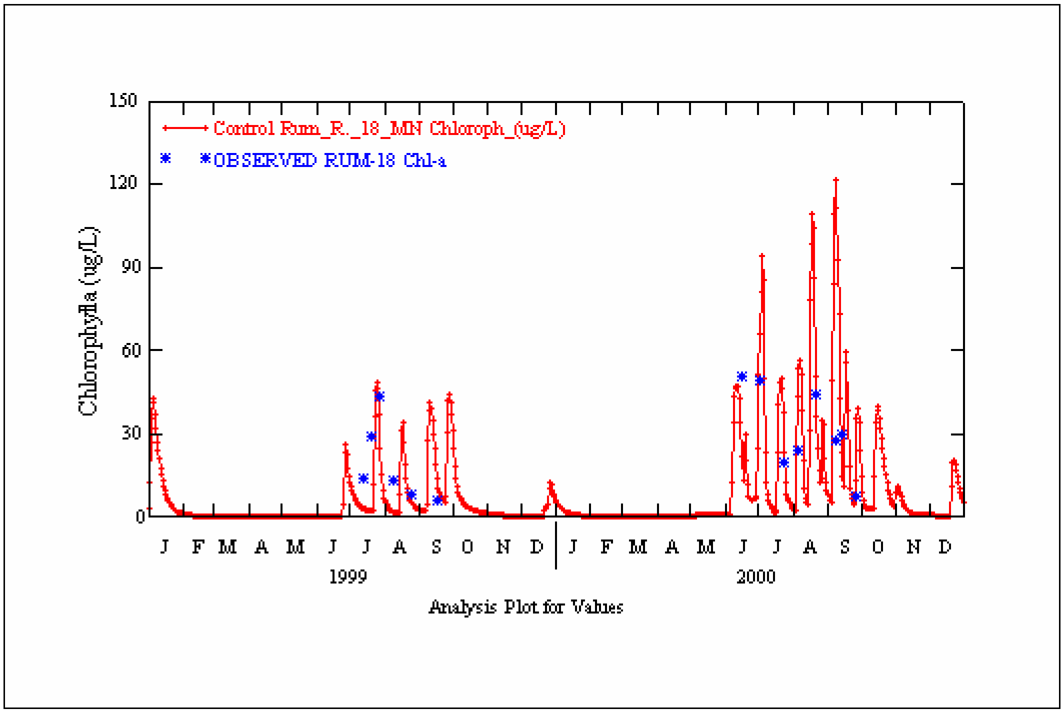


Figure 13. Predicted and observed phytoplankton in Rum River.

Predicted Rum River periphyton are diverse, are dominated by green algae, and exhibit high chlorophyll *a* levels, similar to what was observed (Figures 14, 15, and 3). Note that AQUATOX simulates moss biomass as well as periphyton biomass, and both these contribute to benthic chlorophyll *a*.

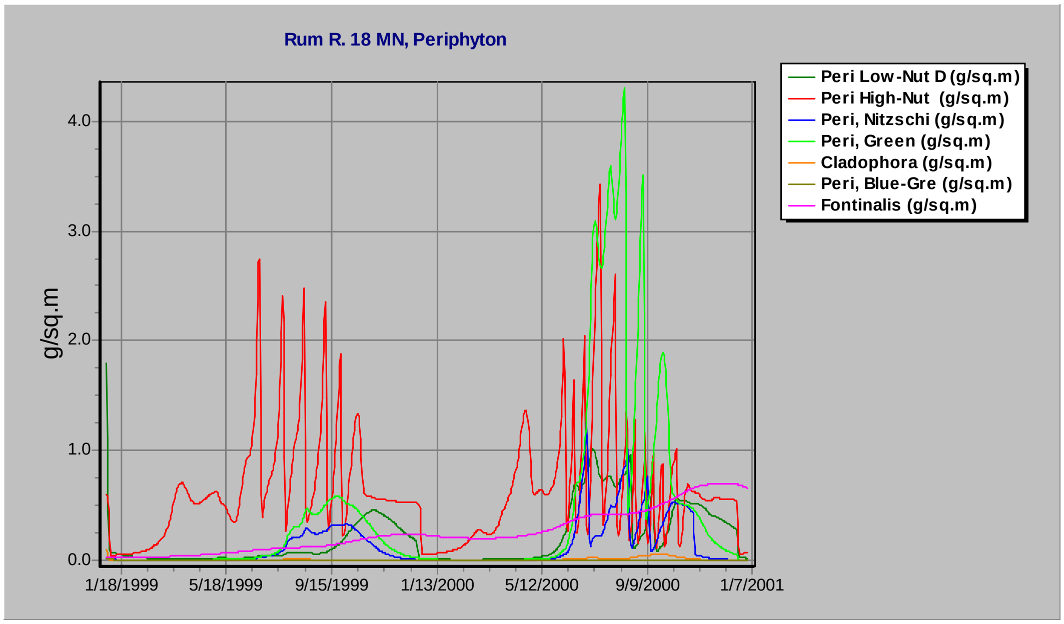


Figure 14. Predicted periphyton composition in Rum River.

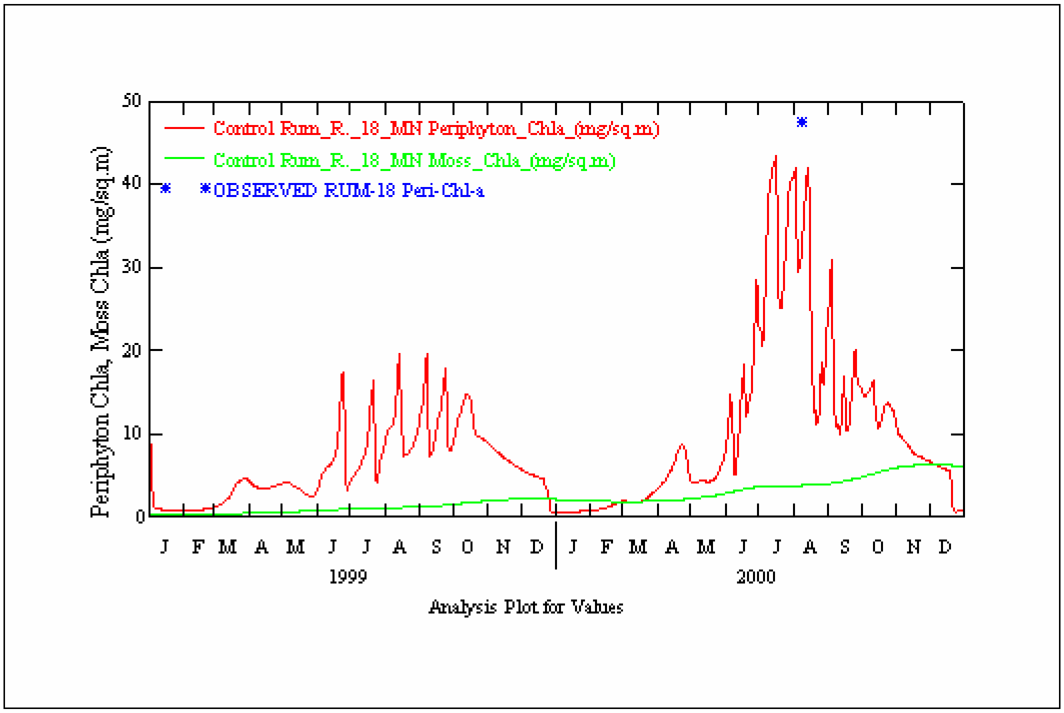


Figure 15. Predicted and observed periphyton and moss chlorophyll *a* in the Rum River.

Predicted Blue Earth River phytoplankton are dominated by blue-greens (Figure 16), similar to what was observed (Figure 6) and cryptomonads. The latter are not as well supported by the observed data, but the samples do not cover the spring and late fall periods. Diatoms are not as important in the simulation as observed.

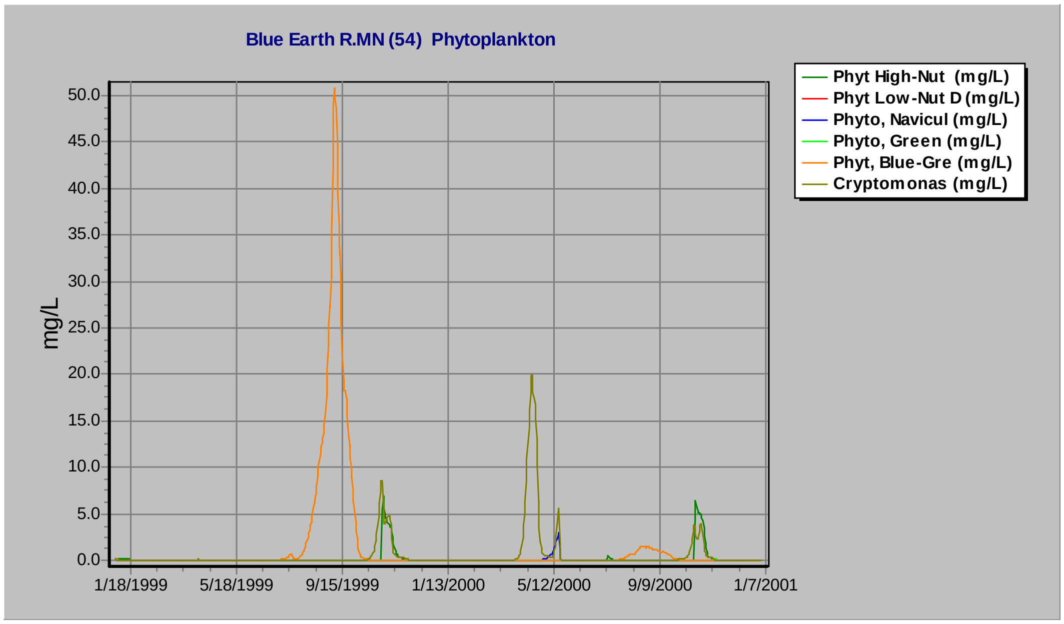


Figure 16. Predicted phytoplankton composition in the Blue Earth River

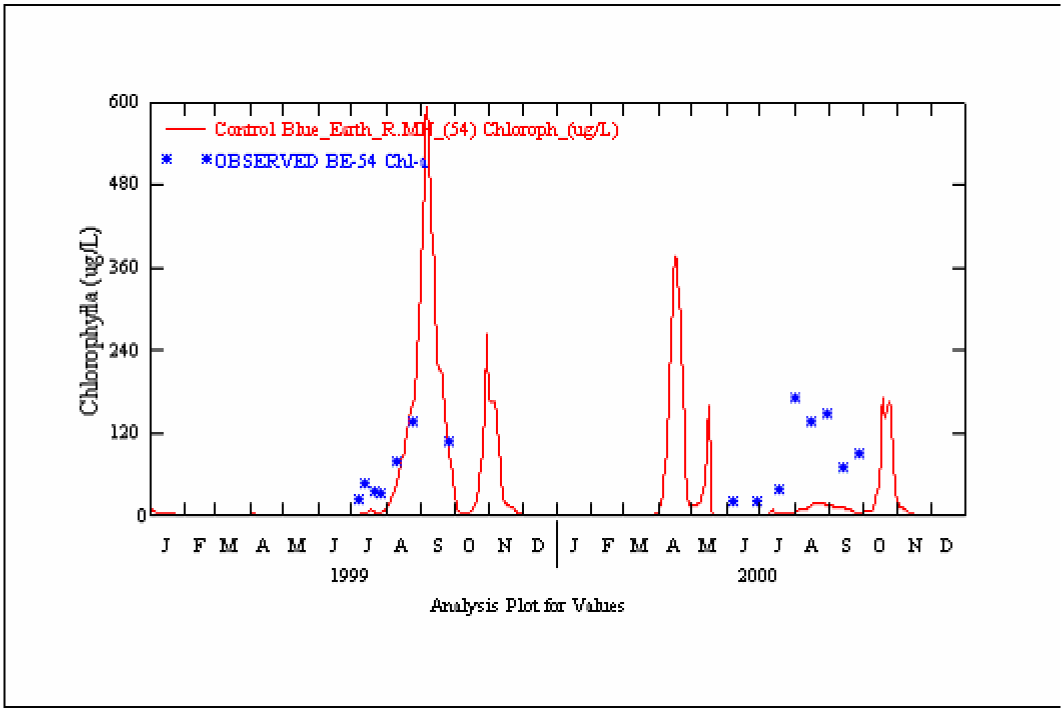


Figure 17. Predicted and observed phytoplankton chlorophyll *a* in Blue Earth River.

The predicted periphyton in Blue Earth River are dominated by high-nutrient diatoms with lesser amounts of blue-greens and greens (Figure 18) as suggested by the observed data (Figure 3). The peak biomass reaches the observed level, but occurs in a different season (Figure 19).

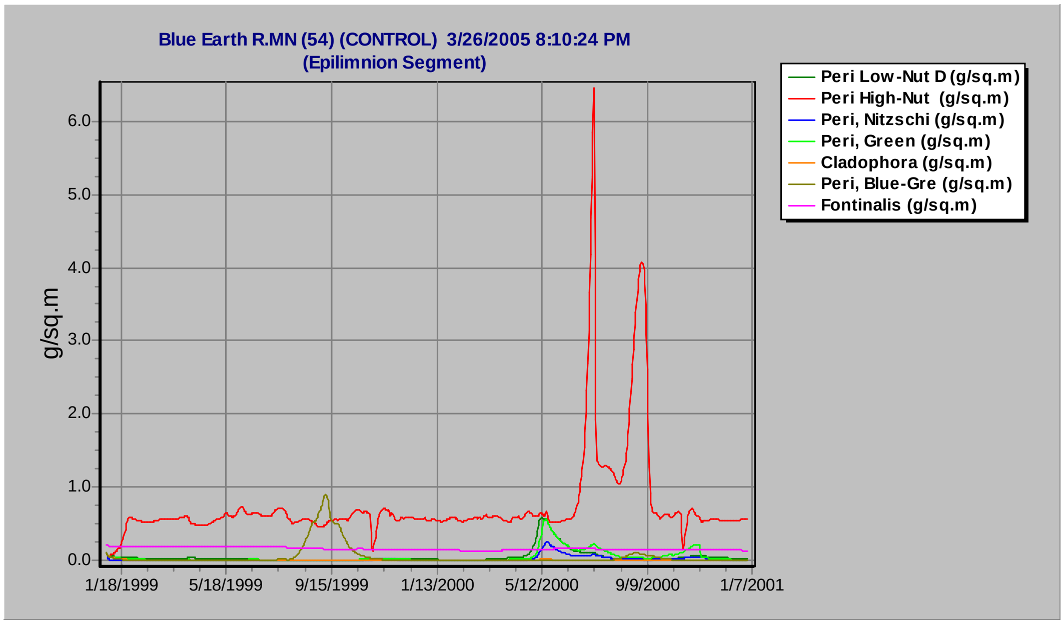


Figure 18. Predicted composition of periphyton in Blue Earth River.

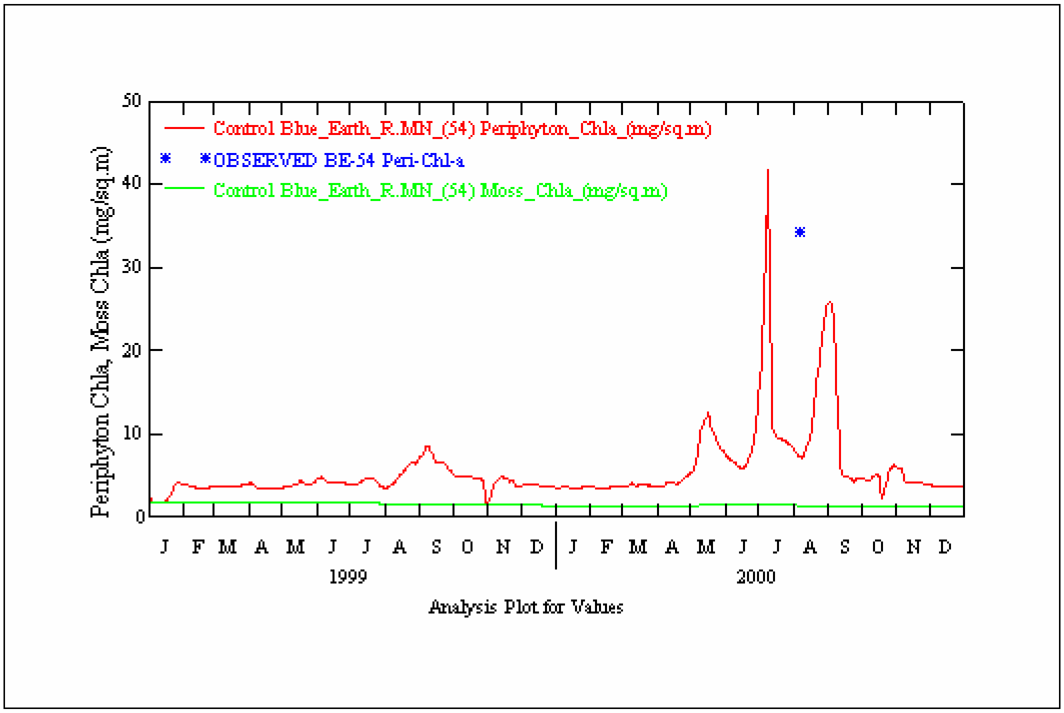


Figure 19. Predicted and observed periphytic chlorophyll *a* in Blue Earth River.

DISCUSSION

A ten-year model run has indicated that model results are reasonable in each year and that this model calibration is stable. Additionally for the two years presented here, the model performs surprisingly well across a wide nutrient and turbidity gradient, as represented by the three Minnesota rivers. Figure 20 makes it quite obvious that phytoplanktonic chlorophyll *a* is far greater in the nutrient-enriched Blue Earth River, followed by the moderately enriched Rum River, with low levels being predicted in the nutrient-poor Crow Wing River.

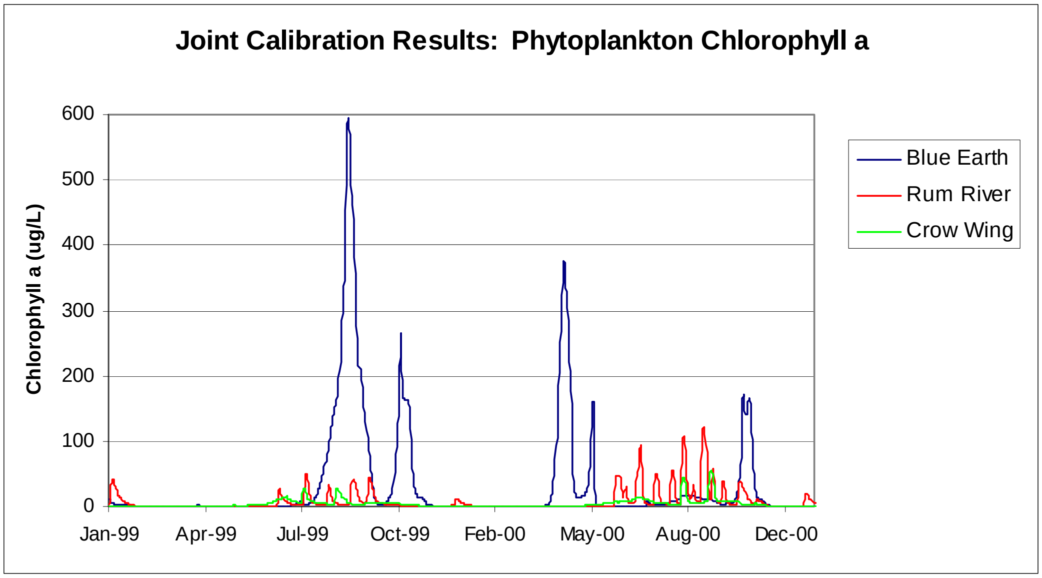


Figure 20 Predicted phytoplanktonic chlorophyll *a* in the Blue Earth, Rum, and Crow Wing Rivers.

Taste- and odor-producing and potentially toxic blue-greens are predicted to be important in the Blue Earth, and unimportant in the Rum and the Crow Wing Rivers (Figure 21).

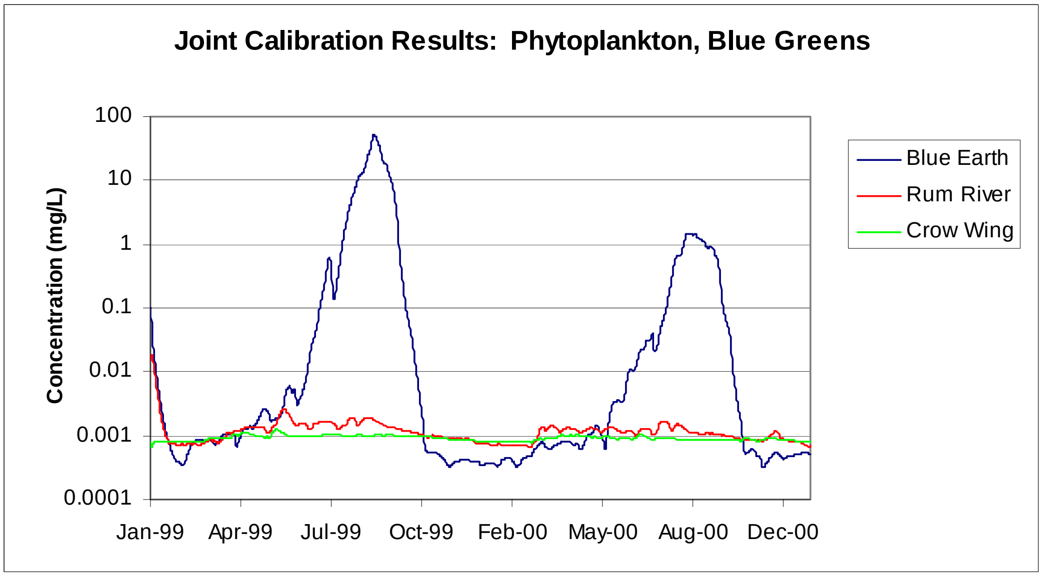


Figure 21. Predicted blue-green chlorophyll *a* in the Blue Earth, Rum, and Crow Wing Rivers.

The pattern of predicted chlorophyll *a* for periphyton is not so obvious. Modeled turbidity in the Blue Earth River prevents significant periphyton blooms in the two year simulation. In the second year, the moderately enriched but clear-water Rum River is predicted to have the highest overall level of periphyton (Figure 22). During 2000, the nutrient-poor, clear-water Crow Wing River and the nutrient-enriched, often turbid Blue Earth River are predicted to have lower levels of periphyton but with occasional blooms. These predictions are in accordance with the single observations of periphyton in the three rivers and with observations across nutrient gradients in other rivers. (High periphyton biomass in 1999 predicted for the Crow Wing River may be a transient condition in the calibration.)

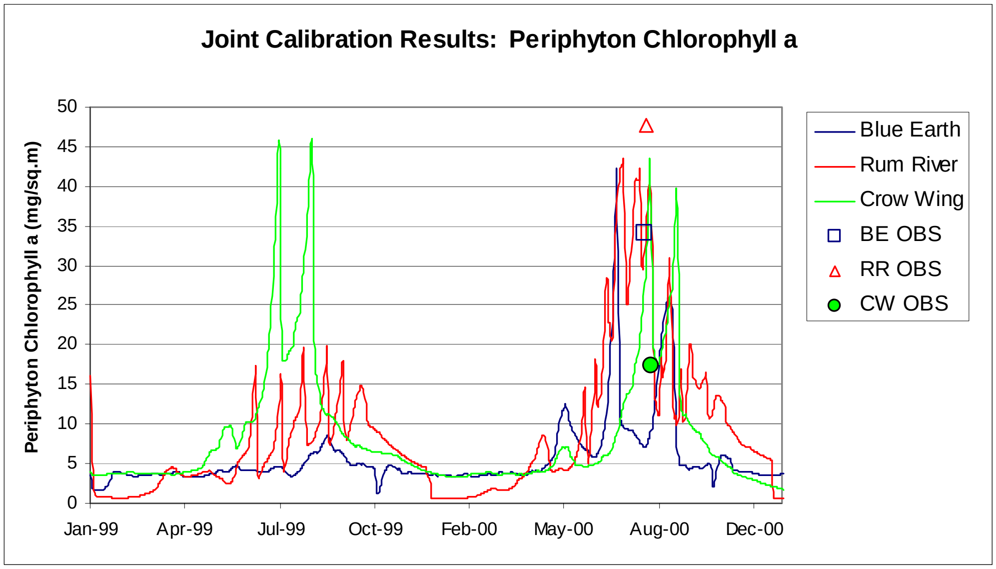


Figure 22. Predicted periphyton chlorophyll *a* in the Blue Earth, Rum, and Crow Wing Rivers.

Model output could be used in the derivation of nutrient water quality criteria in a number of ways, as covered in a companion paper (Carleton *et al.*, 2005). One approach would be to take existing recommendations for mean chlorophyll a concentrations (perhaps from the ecoregional approach) and iteratively run AQUATOX with a range of nutrient reductions until the predicted mean chlorophyll a level is reached. Another option would be to take existing nutrient load reduction recommendations, run AQUATOX with those reductions and see if the chlorophyll a recommendations are met. Alternatively, the model could be used to derive the target itself, perhaps by iteratively running the model with reductions in nutrients and/or suspended sediment, and examining the algal species composition to see if, and at what reduction levels, AQUATOX predicts a shift from high-nutrient species to low-nutrient species.

CONCLUSIONS

Application of the mechanistic ecosystem model AQUATOX linked to the watershed model HSPF provides a promising tool for setting nutrient criteria and for predicting responses to changing conditions as a consequence of watershed management practices. The model is shown to represent a broad range of conditions in Minnesota rivers without site-specific calibration and, as such, is suitable for ecoregional site-specific applications where monitoring data are sparse.

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