NUTRIENT CRITERIA DEVELOPMENT WITH A LINKED MODELING SYSTEM: METHODOLOGY DEVELOPMENT AND DEMONSTRATION

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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 guidance documents and a series of nutrient criteria recommendation 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. The criteria documents established nutrient criteria using percentiles from distributions of monitored nutrient concentrations, designed to reflect reference conditions in each waterbody type (rivers and streams, lakes and reservoirs, wetlands) in each ecoregion. However, as specified in the guidance documents, states and tribes have the option of developing nutrient criteria using other scientifically defensible methods and data. These may come into play, for example, in instances where there is neither a high volume of local data to support an empirical approach, nor an opportunity or justification for applying data and data relationships collected at another similar location.

This paper reports on an example of an approach to developing nutrient criteria that requires less aquatic and biological monitoring data than an empirical approach; instead, relatively minimal data is used in conjunction with a linked mechanistic modeling system that includes a watershed model and an ecological effects model. The approach is illustrated in a demonstration project that uses the watershed model HSPF and the aquatic ecosystem model AQUATOX, which are both part of EPA's BASINS 3.1 (U.S. EPA, 2004) package. AQUATOX is used to link aquatic nutrient concentrations with concentrations of "response variables" (chlorophyll-a, 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. In this paper the approach is discussed, with an emphasis on overall project methodology and study results. An example use of the approach for numeric nutrient water quality criteria development is illustrated. Potential synergies with other, related efforts, such as watershed vulnerability classification, regression-based analyses of stressor-response relationships, and tie-ins with related water quality-related issues, such as Use Attainability Analyses (UAAs) and TMDLs, are discussed. Separate companion papers present the ecological model calibration and validation efforts under alternative nutrient conditions, and the watershed model development and application efforts for two Minnesota watersheds.

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

INTRODUCTION

Under section 303(c) of the Clean Water Act (CWA), States and Tribes are primarily responsible for establishing ambient water quality standards. These standards are required to include scientifically defensible water quality criteria for protecting designated uses of water bodies (*i.e.* streams, rivers, lakes, wetlands, and estuaries). Of the water bodies currently listed by States and Tribes as not meeting designated uses, excessive levels of plant nutrients (various forms of nitrogen and phosphorus) have been identified as a major cause of impairment in roughly half. Unlike toxicants, for which dose-response relationships can be readily measured and used to establish protective concentrations, the link between excessive nutrients and resulting water body impairments can be indirect, and potentially subject to much inter-site variability.

In an attempt to attempt to address confusion resulting from this issue, between 1998 and 2003 the Environmental Protection Agency developed guidance documents (http://www.epa.gov/waterscience/criteria/nutrient/guidance/) and disseminated a series of criteria recommendation documents (*e.g.* U.S. EPA, 2000) designed to help states and tribes develop water quality criteria for nutrients ("stressor variables", *e.g.* N and P, and "response variables", *e.g.* chlorophyll *a* and turbidity). The criteria recommendation documents provided suggested criteria derived using one of two methods based on reference conditions in each water body type in each ecoregion (Figure 1). One method was to select the 75th percentile nutrient concentrations from a set of reference waters (*i.e.* waters with levels of nutrients not affected significantly by anthropogenic inputs) for each water body type and ecoregion. The other method was to select the 25th percentile nutrient concentrations in all of the waters for each water body type and ecoregion (based on an analysis that indicated that the upper 75th percentile for unimpaired waters approximately corresponds to the 25th percentile for all waters). States and Tribes were free to adopt these "reference condition" concentrations as numeric criteria if they chose, but were not required to do so. The guidance and criteria recommendation documents made it clear that these CWA section 304(a) criteria are not laws or regulations but scientifically developed guidance to be used as a starting point by States and Tribes in developing water quality criteria, perhaps through the use of "other scientifically defensible methods and data".

The purpose of the exercise described in this paper is to demonstrate one such method, where publicly available models are used to mechanistically link nutrient stressors to their responses in water bodies for which limited monitoring data exist. For a water body with excessive nutrients, linked modeling of the associated watershed is demonstrated for the purpose of assessing the feasibility of reducing nutrient loads (via implementation of BMPs and other management measures) far enough to attain hypothetical values of the response variable criteria.

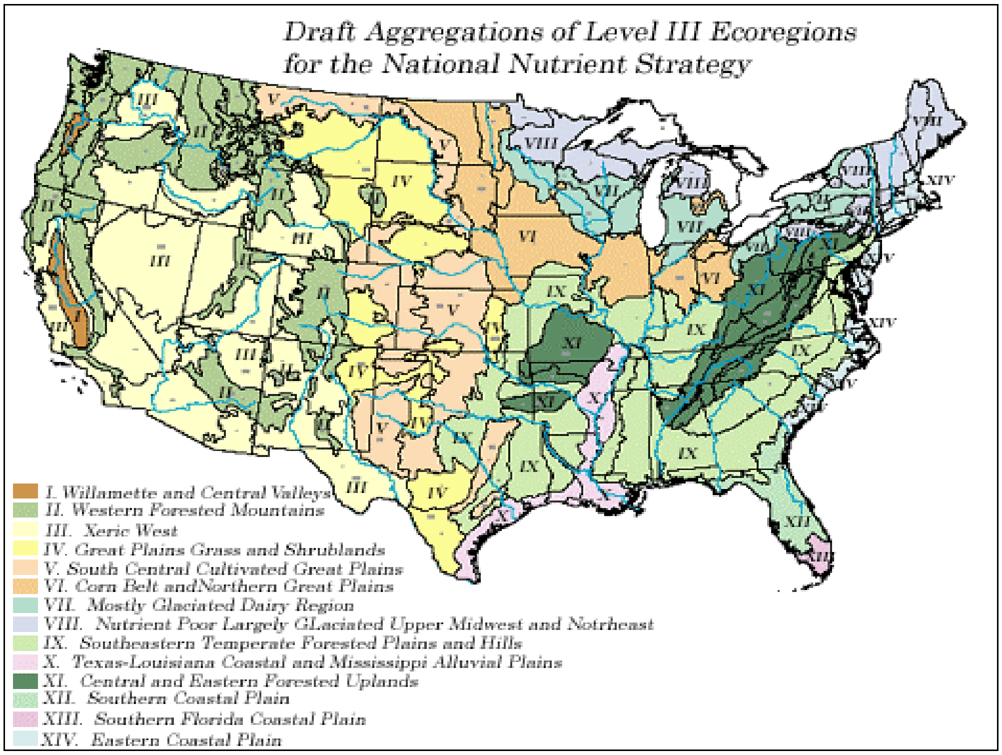

Figure 1. Aggregate ecoregions for nutrient criteria.

DESCRIPTION OF STUDY AND MODELING EXERCISE

One approach to developing nutrient criteria that has been adopted by some States is the implementation of monitoring programs designed for the purpose of assessing statistical correlations between nutrient concentrations and other water quality parameters. For example, the Minnesota Pollution Control Agency (MPCA), with funding in part from a USEPA Nutrient Criteria Development grant (Section 104[b]3), found what they judged to be “significant and predictable relationships” between nutrients, algae, and biochemical oxygen demand in five medium to large rivers, in data collected during 1999 and 2000 (Heiskary and Markus, 2003, 2001). The watersheds of these five rivers are located in different ecoregions, and have differing predominant land uses. As a result, mean total phosphorus (TP) in the five rivers varies over about an order of magnitude, from the relatively low nutrient Crow Wing River, which drains a predominantly forested watershed in the Northern Lakes and Forests ecoregion, to the relatively high nutrient Blue Earth River, which drains an area dominated by row crops in the Western Corn Belt Plains ecoregion of southern Minnesota and northern Iowa. With the cooperation of MPCA, a demonstration modeling project was developed by EPA which takes advantage of this monitoring data for model calibration purposes. Models of the Crow Wing (lowest nutrient), Blue Earth (highest nutrient), and Rum (intermediate nutrient) Rivers (Figure 2) were developed using the ecosystem model AQUATOX, and calibrated simultaneously against available chlorophyll_*a* monitoring data from all three systems, using the same growth and decline parameters to govern a given algal species in each system. Models of the watersheds of the Blue Earth (Figure 3) and Crow Wing (Figure 4) Rivers were also developed in HSPF, calibrated against MPCA's monitoring data (flow, TP, TSS, TN, etc.), then linked to AQUATOX and used to provide upstream boundary conditions to drive the ecosystem simulations. More detailed descriptions of the AQUATOX and HSPF simulations are given in Park *et al.* (2005) and Donigian *et al.* (2005).

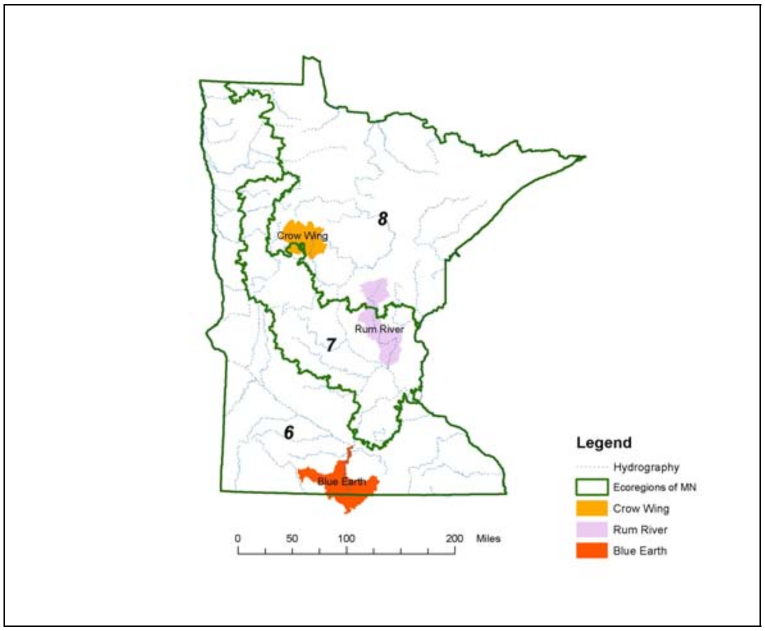

Figure 2. Demonstration Watersheds and EPA Aggregate Nutrient Ecoregions.

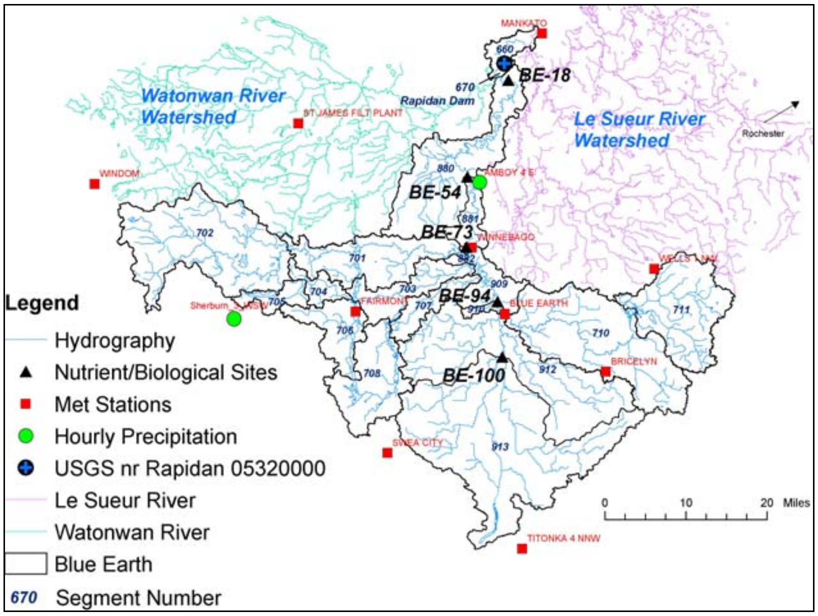

Figure 3. Blue Earth River watershed, segmented for current HSPF implementation.

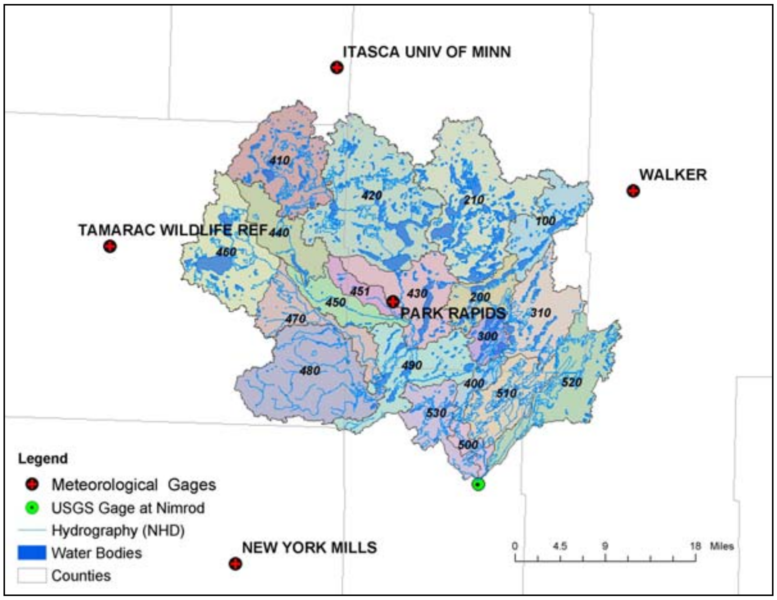

Figure 4. Crow Wing River watershed, with segmentation for HSPF model.

CALIBRATION RESULTS

Blue Earth River

The HSPF model of the Blue Earth River drainage (two year simulation) was successfully calibrated (Donigian *et al*., 2005), achieving general agreement with most of the two years of available monitoring data for TP and TSS (Figures 5 and 6), as well as for TN, NH_3, and NO_3^- (not shown) at sampling location BE54. With the output from this model used to drive a two-year AQUATOX simulation of the algal response at BE54, modeled phytoplankton chlorophyll *a* also achieved general agreement with the monitoring data in terms of peak concentrations, though the timing of the year 2000 peak was not well represented (Figure 7).

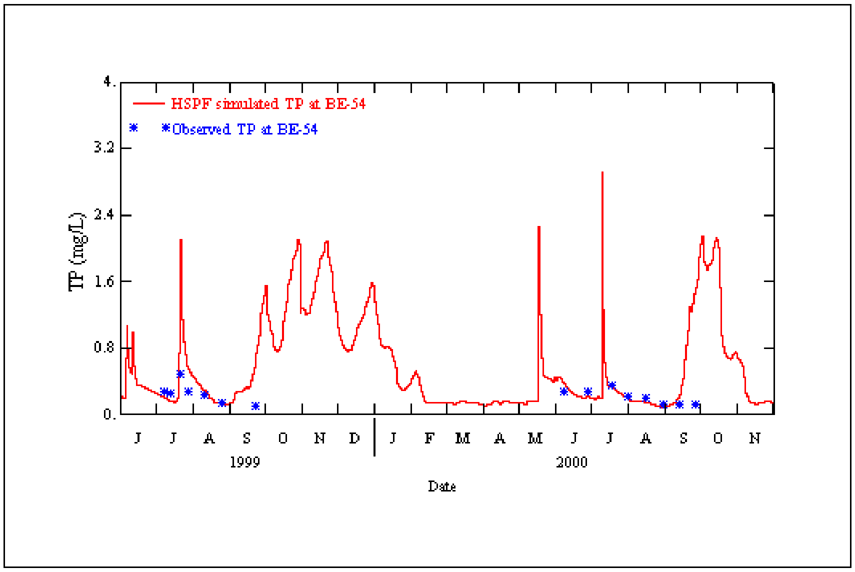

Figure 5. Total P HSPF calibration at Blue Earth River, mile 54 sampling station.

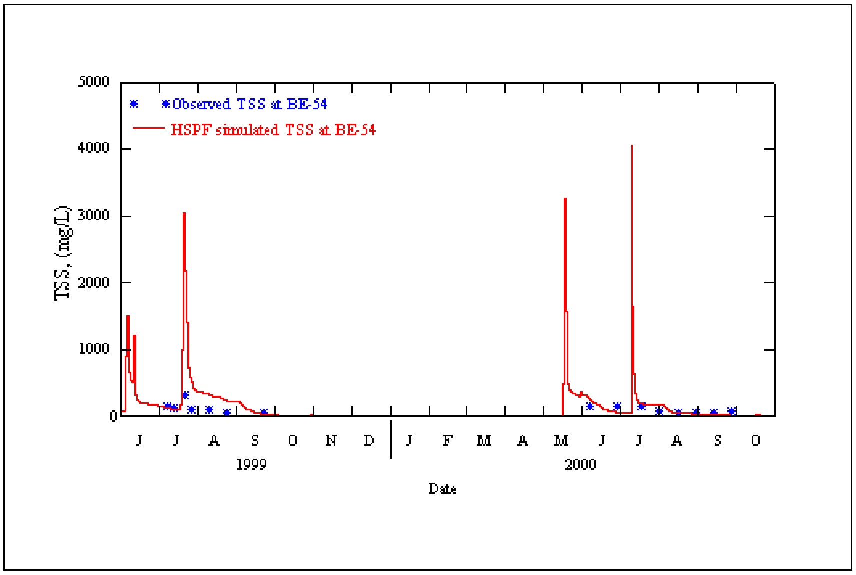

Figure 6. Total Suspended Solids HSPF calibration at Blue Earth River, mile 54 sampling station.

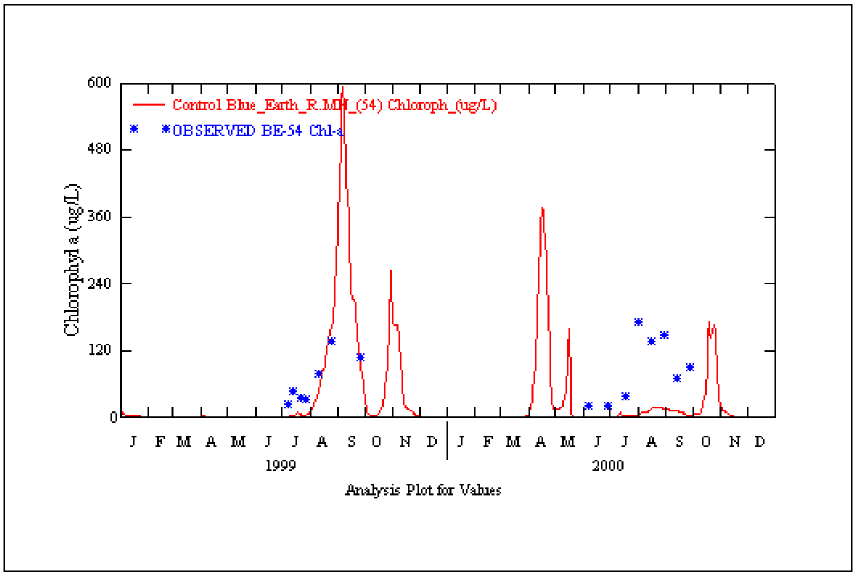

Figure 7. Phytoplankton chlorophyll *a* AQUATOX calibration at Blue Earth River, mile 54 sampling station.

Rum River

Due to resource constraints, an HSPF model of the Rum River watershed was not created. Instead of being driven by HSPF output, as in the case of the Blue Earth and Crow Wing Rivers, the two-year AQUATOX model of the Rum River was driven using interpolated nutrient loadings weighted by daily observed discharge and regression against flow to simulate continuously varying total suspended solids in the simulated reach. AQUATOX was calibrated against the two years of available monitoring data in a simultaneous three-way calibration that also included the Blue Earth and Crow Wing Rivers. As in the Blue Earth simulation, the magnitude of the modeled phytoplankton chlorophyll *a* concentrations achieved general agreement with most of the monitoring data (Figure 8). Note that multiple “sawtooth” peaks in the model trace are due to periphyton sloughing events.

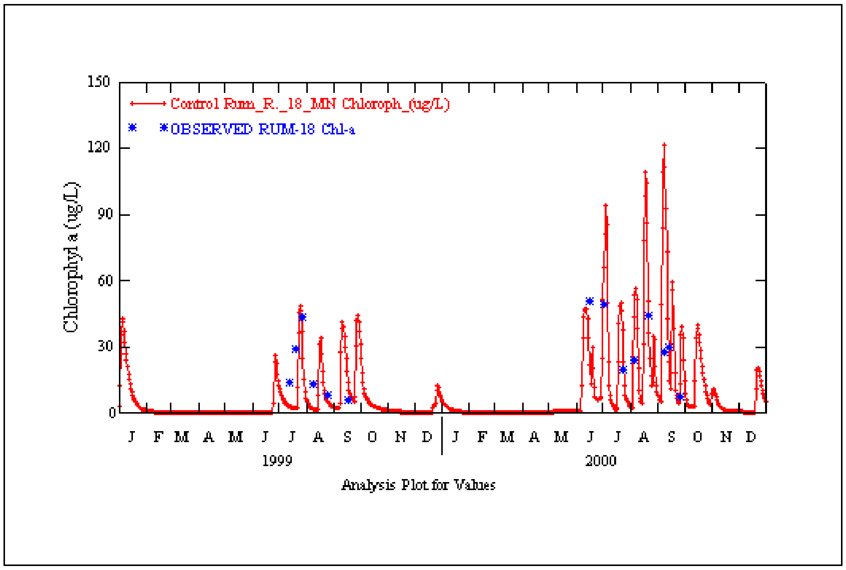

Figure 8. Phytoplankton chlorophyll *a* AQUATOX calibration at Rum River, mile 18 sampling station.

Crow Wing River

As with the Blue Earth simulation, the HSPF model of the Crow Wing River (two-year simulation) was calibrated to achieve general agreement with the available monitoring data at upstream sampling location “CWR-72.3” for TP and TSS (Figures 9 and 10), as well as for other nutrient species. With the output from this model used to drive a two-year AQUATOX simulation of the algal response, modeled phytoplankton chlorophyll *a* also achieved general agreement with the monitoring data (Figure 11).

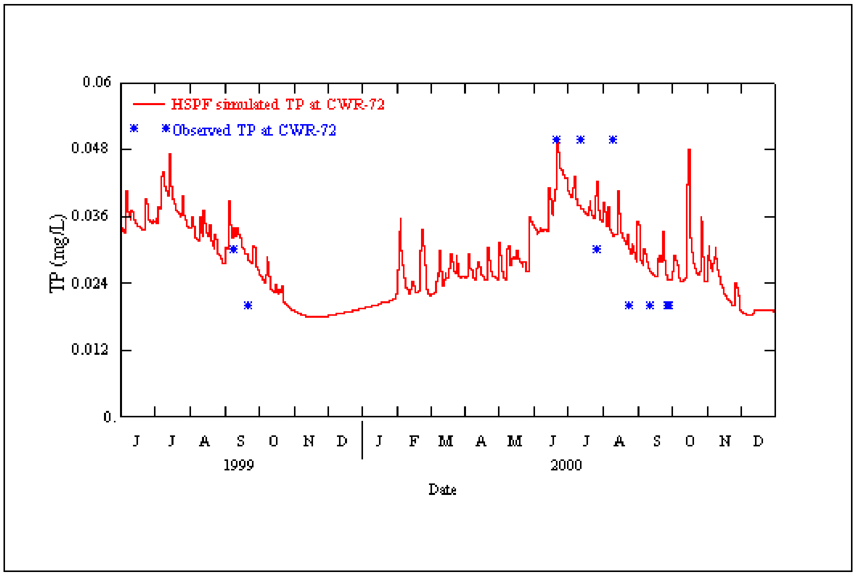

Figure 9. Total P HSPF calibration at Crow Wing River, mile 72.3 sampling station.

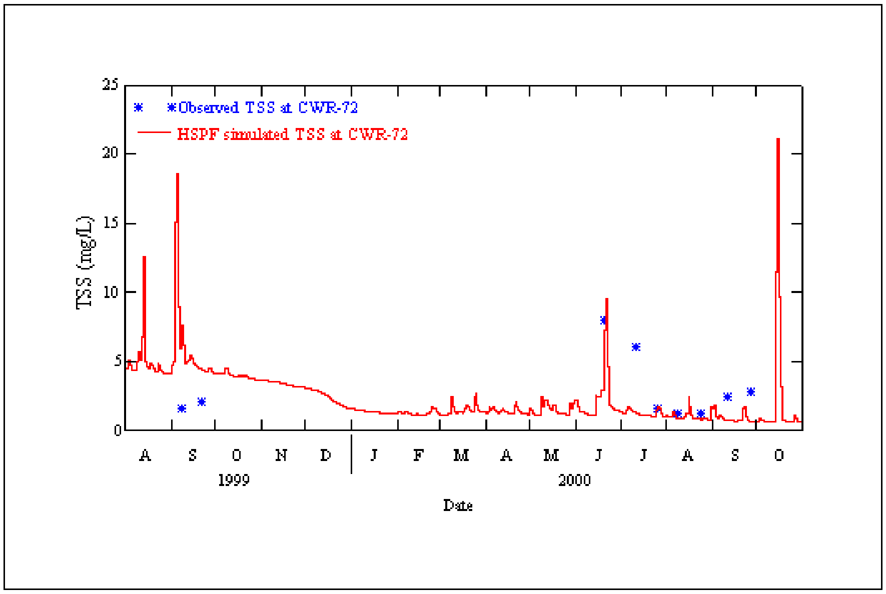

Figure 10. Total Suspended Solids HSPF calibration at Crow Wing River, upstream (mile 72.3) sampling station.

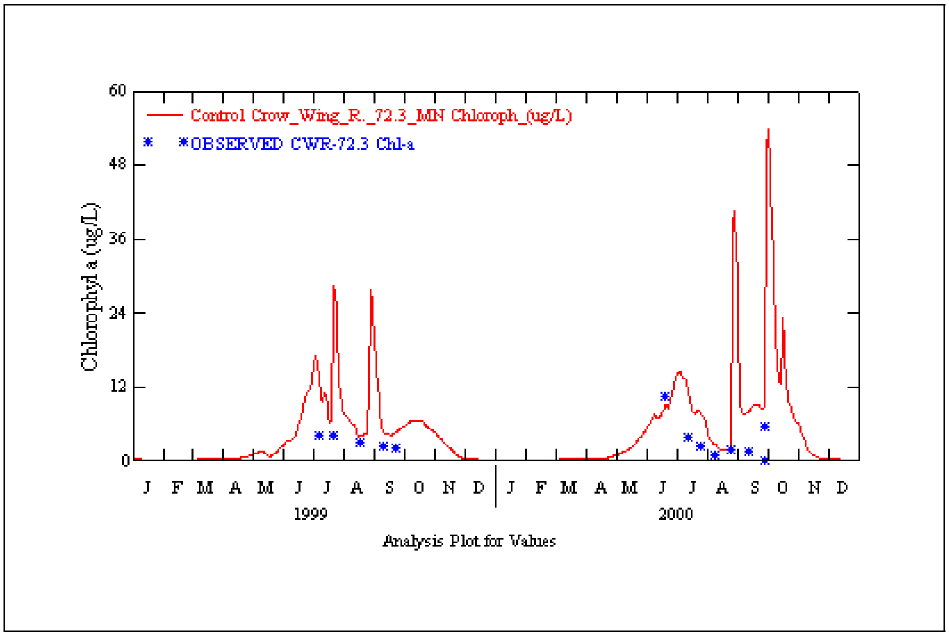

Figure 11. Phytoplankton chlorophyll *a* AQUATOX calibration at Crow Wing River, upstream (mile 72.3) sampling station.

The simultaneous calibration of AQUATOX phytoplankton chlorophyll *a* simulations across the order-of-magnitude nutrient gradient represented by the three modeled rivers suggests that the selected model phytoplankton parameters are robust under variable nutrient conditions. This increases confidence that when parameterized in this manner, AQUATOX is capable of simulating the algal response to changing nutrient conditions within a single system. In the relatively high-nutrient Blue Earth River, AQUATOX can be expected to reasonably simulate changing phytoplankton and chlorophyll *a* concentrations that would result from nutrient reductions brought about by management changes in the watershed. More generally, with linked

HSPF and AQUATOX, a modeler can estimate levels of Best Management Practice (BMP) implementation that might be needed in order to achieve target chlorophyll *a* water column concentrations- or determine whether given water quality targets are likely to be attainable at all.

OPTIONS FOR USING MODELS IN CRITERIA DEVELOPMENT

Two hypothetical examples are presented below that show how States and Tribes might use linked watershed and ecological effects models to help develop nutrient water quality criteria. Both methods begin with a water column chlorophyll *a* concentration deemed by a State or Tribe to be acceptable, then employ AQUATOX simulations to determine nutrient concentrations that would achieve these response variable concentrations. Both methods are developed using the Blue Earth River as an example of a water body in which nutrient reductions might be desired. Modified versions of the HSPF model of the Blue Earth are also developed which reflect BMPs and management scenarios currently being implemented within the watershed to control nutrient and sediment runoff. Resulting reductions in modeled constituent concentrations are propagated through the linked AQUATOX model to determine levels of BMP implementation that would be needed to achieve the hypothetical response variable criteria.

Criteria Development Example Method 1

This method begins with the presumption that the State (Minnesota) has accepted the 304(a) reference condition chlorophyll *a* concentration (but not necessarily the corresponding stressor variable values) to be one of the response variable criteria for stream and rivers in the relevant ecoregion (47 for the Blue Earth River watershed). The percentile based criteria for nutrient stressor and response variables for Level III ecoregion 47 are listed in Table 1. The chlorophyll *a* monitoring data against which AQUATOX was calibrated were analyzed using the spectrophotometric method (Steve Heiskary, MPCA, personal communication), therefore the relevant criterion value is 7.85 : g/L. This value is assumed to apply to long-term (*i.e.* at least annual) mean concentrations in the River.

Table 1. Excerpted from Table 3b, on p. 16 of U.S. EPA (2000), "Reference conditions for Level III Ecoregion 47, from Ambient Water Quality Criteria Recommendations…" (Ecoregion VI), EPA822-B-00-017.

Parameter	# of streams	Reported min	Reported max	25th Percentile (all seasons)
TKN (mg/L)	136	0.57	4.42	0.65
NO2 + NO3 (mg/L)	141	0.083	9.6	1.965
TN (mg/L) calculated	NA	0.653	14.02	2.615
TN (mg/L)- reported	32	1.65	10.06	3.26
TP (ug/L)	187	11.25	1720	118.13
Turbidity (NTU)	32	4	160	15
Turbidity (FTU)	74	0.975	178	7.69
Turbidity (JCU)	56	4.23	116.5	10.15
Chl a (ug/L)- fluorometric method	24	1.8	45.2	4.4
Chl a (ug/L)-spectrophotometric method	25	3.76	90.6	**7.85**
Chl a (ug/L)- trichromatic method	3	9.38	31.0	9.38

The mean chlorophyll *a* concentration generated by the calibrated AQUATOX model of the Blue Earth River for a two-year simulation covering the years 1999 and 2000 was 31.97 : g/L, and the mean chlorophyll *a* over an eleven-year simulation covering 1990 through 2000 was 10.95 : g/L. The corresponding mean TP, TSS and NO_3^- over an eleven-year simulation (1990-2000) with the calibrated HSPF model were 266 : g/L, 95.7 mg/L, and 8.7 : g/L, respectively. To determine approximate nutrient reductions necessary to bring the mean chlorophyll *a* concentration for the period 1990 – 2000 to below the ecoregion based value of 7.85 : g/L, two-year (1999 – 2000) AQUATOX simulations were run using fractional multipliers in increments of 0.2 applied to the HSPF generated TP and TSS loads (Table 2). The table shows resulting modeled mean chlorophyll *a* concentrations for the two-year period, and mean chlorophyll *a* over the eleven-year period, estimated using the assumption of a fixed ratio between two-year and eleven-year mean values.

Table 2 also shows two-year and eleven-year results for a scenario that includes a 35 percent nitrate load reduction, reflective of management goals that have been established for the watershed (described in next section). The close correspondence between the modeled and estimated mean chlorophyll *a* for this scenario suggests that the estimated values are reasonable approximations of modeled values. The results in Table 2 suggest that a reduction in TP and TSS on the order of between 20 and 40 percent is required in order to bring the long-term mean value of the response variable chlorophyll *a* in the Blue Earth River to below 7.85 : g/L. By contrast, a reduction of 55 percent would be needed to bring the mean TP to below the ecoregion-based value (118.13 : g/L) for this stressor variable.

Table 2. AQUATOX results for calibrated Blue earth River model, with multipliers applied to HSPF input loads.

		1999-2000	1990-2000	1990-2000
TP & TSS multiplier	NO_3^- multiplier	Mean chl_*a* (: g/L)	Mean chl_*a* (: g/L)	Estimated Mean chl_*a* (: g/L)
1.0	1.0	31.97	10.95	
0.8	1.0	23.74		*8.13*
0.6	1.0	19.92		*6.82*
0.4	1.0	18.39		*6.30*
0.2	1.0	15.75		*5.39*
0.4	0.35	16.35	5.92	*5.60*

Criteria Development Example Method 2

In the second method, AQUATOX simulations are used to estimate the phytoplankton chlorophyll *a* concentration corresponding roughly to the point at which a shift between high and low nutrient phytoplankton species may occur. The multiple AQUATOX simulations at various nutrient loadings described in method 1 were examined for phytoplankton species abundance to look for overall trends (Figures 12, 13). Model results predict a large decrease in the absolute and relative abundances of blue-green algae and high-nutrient diatoms with decreases of between 20 and 40 percent in TP and TSS loadings, consistent with the results of method 1. For purposes of this exercise, the chlorophyll *a* value associated with a 30 percent TP/TSS reduction (*i.e.* the midpoint between 20 and 40 percent reduction) was chosen as the target for the response variable. This value, 7.5 : g/L, which was estimated by averaging the mean chlorophyll *a* from the 20 and 40 percent reduction scenarios, is very close to the ecoregion-based criterion of 7.85 : g/L.

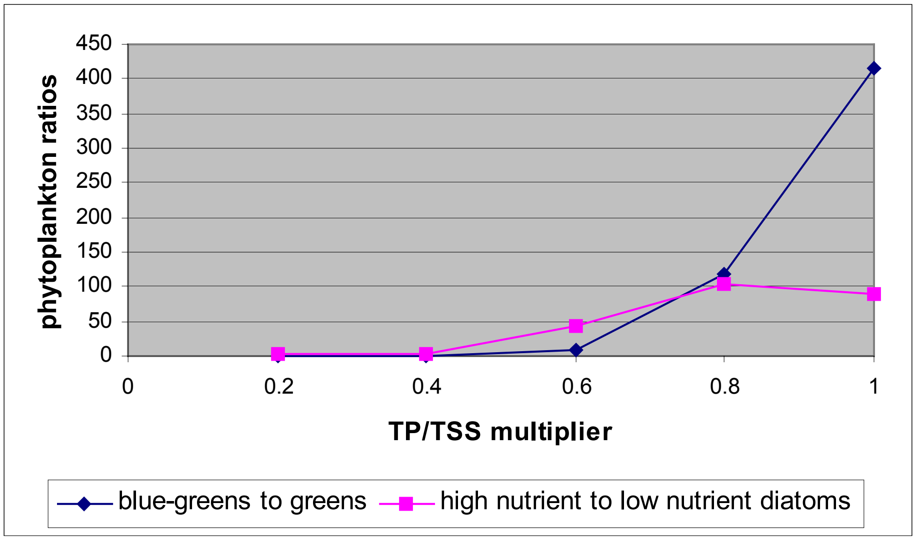

Figure 12. Concentration ratios of blue-green to green algae, and high-nutrient to low-nutrient diatoms in AQUATOX simulations with various TP & TSS load multipliers.

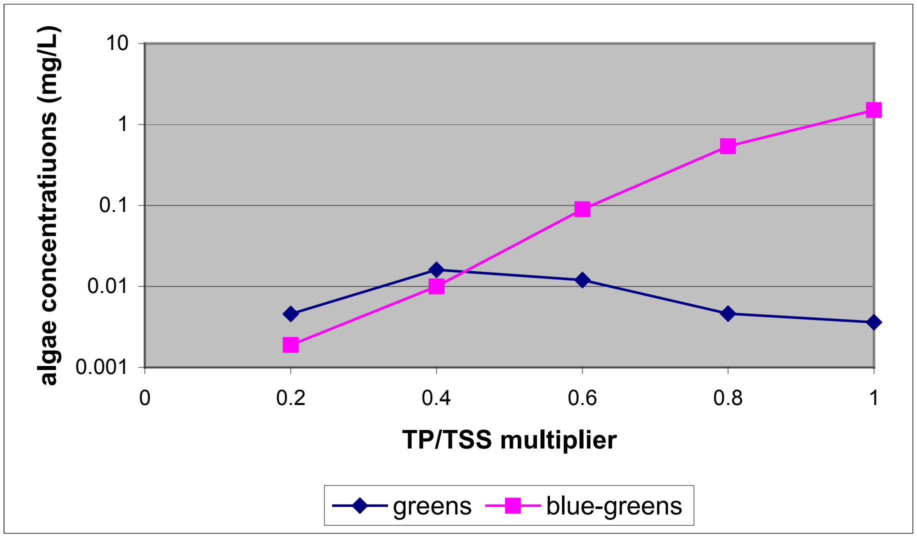

Figure 13. Concentrations (log scale) of green and blue-green algae in AQUATOX simulations with various TP & TSS load multipliers.

BLUE EARTH MITIGATION

The Blue Earth River is widely recognized as being enriched in nutrients and suspended sediments. In May, 2004 the USDA selected the Blue Earth River watershed as one of 18 watersheds throughout the U.S. to receive funding under the Conservation Security Program (CSP) to mitigate agricultural runoff. The Greater Blue Earth watershed (which includes LeSueur and Mankato River drainages) has also been the recipient of grant money from EPA to fund watershed restoration activities.

In October 2000, MPCA released a diagnostic report ("Clean water partnership #1943", available on-line at http://mrbdc.mnsu.edu/reports/bluearth/cwp30/cwp30.html) that summarized water quality impairments in the Blue Earth River watershed. The report included an implementation plan for improving water quality that was developed with citizen involvement (the "WILL committee"), and which specified reduction goals of 40% for TP and TSS, and 35% for NO_3^- in the Blue Earth River. The plan identified "priority management areas" within the watershed for targeted pollution control activities, and included a list of management strategies to be implemented in these areas. Of the items on the list, the impacts of the following were selected as potentially amenable to quantification by modification of select parameters in the HSPF model of the watershed:

- Riparian/ditch buffers
- Streambank stabilization
- Wetland restoration
- Agricultural BMPs/crop residue management
- Surface tile buffers
- Feedlot upgrades
- Comprehensive nutrient management

BMP REPRESENTATION WITH HSPF

In order to represent potential BMP impacts with HSPF for the Blue Earth Watershed, it is necessary to identify which BMPs will affect which nonpoint pollutant sources, establish how the model will implement or approximate the BMP effects, and what level(s) of BMP implementation will be evaluated. The HSPF BMP Module was used to represent the alternative BMP strategies listed above. The BMP Module uses simple 'removal efficiencies' (RE) to calculate the load reductions expected from the affected land areas. Although HSPF provides a variety of flexible options for representing BMPs, the simple RE approach with the BMP Module was deemed appropriate for the Blue Earth model due to the large areas of the model segments, the empirical washoff formulations for the loading calculations, and the overall planning nature of the evaluation. In the future, with finer spatial definition of model segments, specific practices, such as grass waterways, riparian/forest buffers, farm ponds/tile risers, crop residues, etc. can be explicitly modeled to allow more detailed evaluations.

Thus, the steps required to represent BMP strategies within the Blue Earth Watershed model are as follows:

1. Identify correspondence between BMP strategies and nonpoint pollutant sources within the Blue Earth HSPF model. Table 3 lists the BMP strategies and shows the modeled nonpoint pollutant sources that would be impacted by each strategy. Four of the seven BMP strategies could be applied to reduce loadings from the cropland Hi-Till and Lo-Till categories. Feedlot upgrades, surface tile buffers, and streambank stabilization would only impact loadings from those sources. Since surface tiles are represented as an 'additional' pollutant source, calculated as a function of the interflow rate, the buffers would serve to reduce loads from that source. Also, streambank stabilization is represented as a means of reducing 'bank and bluff'

erosion which, in the model, is calculated as an additional sediment load only for selected susceptible stream reaches.

2. Estimate Removal Efficiencies (RE) for each BMP strategy and each nonpoint source modeled pollutant. Table 4 shows the REs selected for each BMP strategy; the RE values are discussed further below.

3. Define 'implementation levels' reflecting the percentage of each model segment area, or source, that will be controlled or affected by each BMP strategy, e.g. a 30% implementation for Ag BMPs/CRM might mean that 30% of both cropland categories (Hi-Till and Lo-Till) will have these practices implemented. By evaluating the impacts of alternative implementation levels, it is possible to identify the extent of implementation needed to reach a water quality standard, attain a TMDL target load, and/or achieve a nutrient water quality criteria.

Table 3. Correspondence Between BMP Strategies and Nonpoint Pollutant Sources

	Major NPS Sources In Blue Earth Watershed Model				
BMP Strategies	Hi-Till	Lo-Till	Feedlots	Tiles	Bank/Bluff
Riparian/Ditch Buffers	X	X			
Streambank Stabilization					X
Wetland Restoration	X	X			
Ag BMPs/Crop Residue Management	X	X			
Surface Tile Buffers				X	
Feedlot Upgrades			X		
Comprehensive Nutrient Management	X	X			

DEVELOPMENT OF REDUCTION FACTORS

In most cases, model modifications to reflect management activities take the form of simple reduction factors (*i.e.* removal efficiencies) for specific water quality constituents. These reduction factors are empirically derived multipliers, which are applied uniformly to constituent loads during transfer between model segments, irrespective of flow regime, season, or environmental conditions. In the real world of course, BMP and management measure efficiency will in general vary both spatially and temporally as a function of numerous interacting physical, biological, and chemical factors.

Reduction factors for various BMPs and management strategies in the Blue Earth River watershed (Table 4) were developed primarily through review of a variety of relevant literature sources. Values in Table 4 for the most part represent approximate "central tendency" or typical reported values for each type of practice. In the case of wetland restoration, the process was a bit more involved and is discussed in more detail in the following section.

Table 4. Removal efficiencies for selected BMP strategies in the Blue Earth River watershed.

	% Removal Efficiencies for Identified Constituents							
BMP Strategies (References)	TSS	BOD	NH3	NO3	ORG N	PO4	ORG P	ORG C
Riparian/Ditch Buffers (1, 2, 4, 6)	70	30	45	30	50	40	60	50
Streambank Stabilization	90	0	0	0	0	0	0	0
Wetland Restoration (7)	74	70	33	70	50	35	60	50
Ag BMPs/Crop Residue Management (4, 5, 6)	75	40	40	35	60	45	70	50
Surface Tile Buffers (2, 3, 6)	65	25	0	0	0	30	0	0
Feedlot Upgrades (2, 3, 6)	65	25	35	10	40	30	50	40
Comprehensive Nutrient Management (4, 5, 6)	0	40	40	50	30	40	30	10
Ag BMPs/Crop Residue Management + Comprehensive Nutrient Management	75	64	64	68	72	67	79	55

References:
1. EPA, 1999. Preliminary Data Summary of Urban Stormwater BMPs.
2. Literature Review for HSPF BMP Module (A. Donigian, Personal Comm.)
3. Winer, 2000. Center for Watershed Protection
4. AQUA TERRA Consultants, 1993.
5. Hamlett and Epps (1994)
6. EPA, 2003.
7. Carleton et al., 2001

The reference sources for the REs in Table 4 are briefly listed at the bottom of the table, with complete citations provided in the References. These literature sources cover a wide range of studies involving literature data reviews, complied databases, modeling efforts, site-specific studies, and even urban stormwater literature since detention processes are universal irrespective of the load source. In reviewing these values, the following should be noted:

a) Except for streambank stabilization and surface tile buffers, all the BMP strategies can affect nonpoint loadings for each of the constituents listed in Table 4. Thus, REs were required for each of those constituents.
b) Streambank stabilization only impacts bank/bluff erosion which only contributes additional TSS loads, and surface tile buffers only contribute TSS, BOD, and PO4, in the current model application. Thus those are the only REs required for these strategies.
c) The REs for riparian/ditch buffers are derived primarily from grass/vegetated waterways values from both agricultural and urban data reports.
d) Feedlot upgrades and surface tile buffers are derived from REs from dry detention ponds

for both agricultural and urban studies.

e) Ag BMP/Crop Residue Management and Comprehensive Nutrient Management values are derived from the EPA Nonpoint Source Handbook, agricultural studies in PA, and modeling studies.

f) The last BMP strategy is a composite of the Ag BMP/CRM and Comprehensive Nutrient Management being applied to the same land area. These REs are calculated as follows:

$$RE_{\text{composite }1,2} = 1 - ((1 - RE_1) * (1 - RE_2))$$

Where:

$RE_{\text{composite }1,2}$ = Effective RE for 2 BMP strategies in series
RE_1 = RE for Ag BMP/CRM
RE_2 = RE for Comprehensive Nutrient Management

Wetland Restoration

Although the predominant land use in the Blue Earth River watershed is now row crop agriculture, the land was historically part of the tallgrass prairie biome, and was widely covered with wetlands. To support the growing of row crops, the land was extensively tile-drained and ditched in the last centuries, with the result that most of the historical wetlands are no longer present. It is now known that wetlands serve numerous beneficial purposes, including the removal or sequestration of pollutants from flowing water (Mitsch and Gosselink, 2000). Studies have specifically documented the ability of restored northern prairie wetlands to serve as sinks for nutrients in wastewater (White *et al.*, 2000). In recognition of the manifold importance of wetlands, a multi-stakeholder group has developed a GIS data layer of “restorable wetlands” in Minnesota, based in part upon soils information (Figure 14), to enable and assist local wetland restoration activities (ftp://mrbdc.mnsu.edu/pub/bluearth/cwp/landcap30.zip). Information from this layer was used to help develop wetland reduction factors for the Blue Earth River watershed.

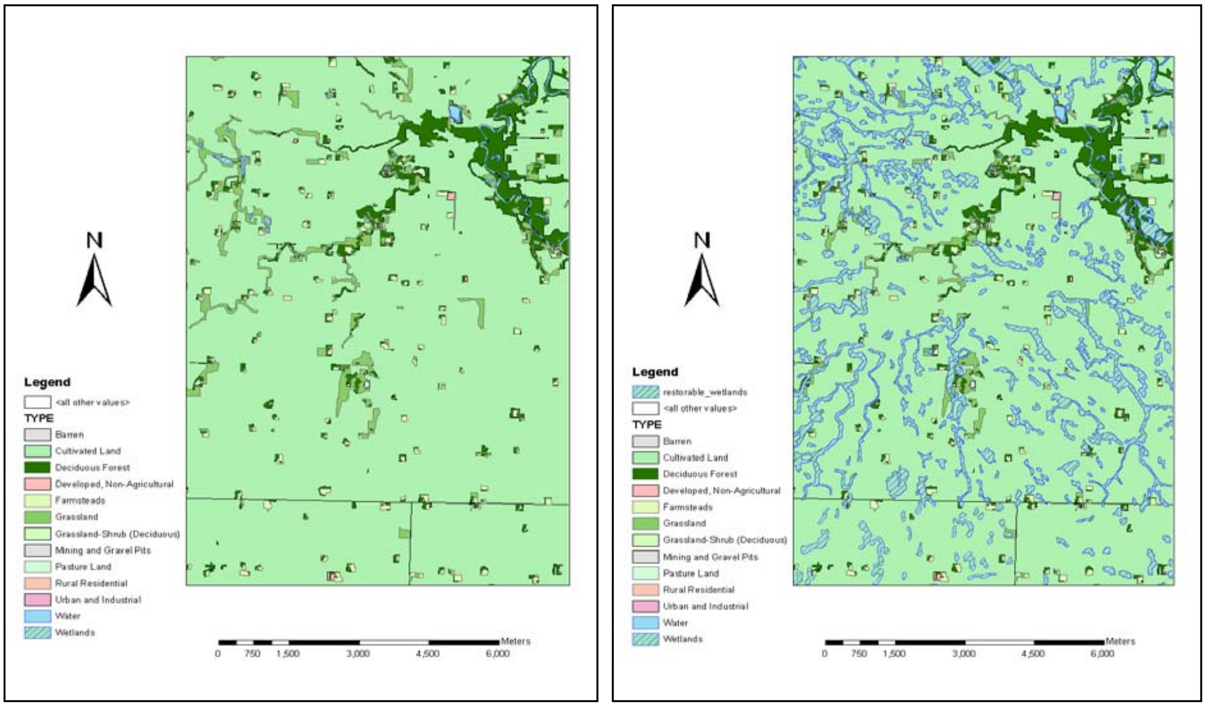

Figure 14. Example portion of Blue Earth River watershed showing current land use/land cover (left), and with "restorable wetlands" data layer overlaid (right). Blue Earth River is in upper right.

The development of mathematical approaches for predicting or describing pollutant removal in wetlands is an area of ongoing research. Some of the simplest existing approaches rely upon empirical descriptions of performance gleaned from field study data. One such approach relates long-term performance to the relative areas of wetlands and their contributing watersheds, under the presumption that the bigger the wetland-to-watershed area ratio, the greater the expected average percent removal of inflowing pollutants. For this exercise, data from a large number of runoff-treatment wetland studies (Figures 15 and 16) summarized by Carleton *et al.* (2000) were used to develop pollutant-specific reduction factors for different constituents, on the basis of wetland-to-watershed area ratio information. Several of the cited studies were actually conducted in Minnesota.

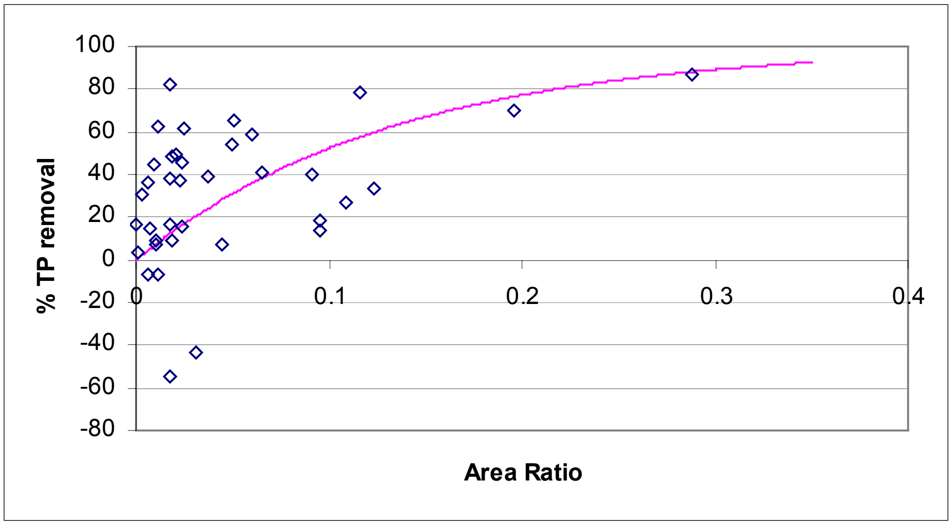

Figure 15. Nonlinear regression: % TP removed in reviewed studies, as a function of wetland-to-watershed area ratio.

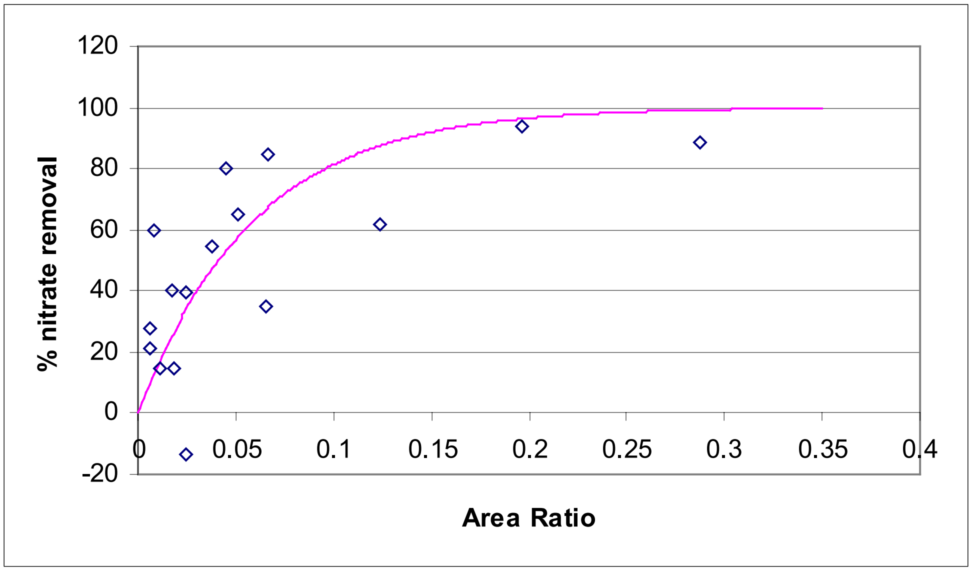

Figure 16. Nonlinear regression: % NO_3^- removed in reviewed studies, as a function of wetland-to-watershed area ratio.

To develop reduction factors for wetlands, the performance data summarized in Carleton *et al.* (2000) were plotted as % removal *vs.* area ratio. Non-linear least squares optimization was used to fit the following equation to the data for each constituent of interest:

$$\%RE = 100\left(1 - e^{-kx}\right)$$

where %RE is percent removal, x = (wetland area)/(watershed area), and k is a fitting coefficient optimized via regression. Total restorable wetland area was extracted from the restorable wetlands data layer, and total cultivated land area after wetland restoration was extracted from a land use/cover data layer. The ratio of these two values for the entire watershed was approximately 0.07, which was then plugged in as ‘x’ in the above equation to estimate reduction factors for each constituent.

OPERATIONAL PROCEDURES FOR GENERATING ALTERNATIVE WATERSHED SCENARIOS

The approach for generating and analyzing alternative scenarios for the Blue Earth HSPF application involves the integrated use of the BMP and REPORT modules of HSPF, and GenScn, and is implemented as a semi-automated process within a Microsoft Excel framework. Generating the HSPF input files for the alternative scenarios involves performing the following steps within a tailored Excel workbook and transferring the results to the HSPF UCI file:

1. Assign implementation levels for each scenario for the suite of BMP strategies (listed in Table 3) that would be implemented on the major nonpoint load sources within the watershed.
2. Calculate an ‘effective’ removal efficiency (RE) based on the implementation levels assigned and the REs (from Table 4) for the individual BMPs selected for implementation, for each constituents determined to be impacted by the BMPs.
3. Establish the division of the model segment areas into those areas served by the BMP, those areas not served by the BMP, and subsequent connection of both area types to the downstream receiving reach within the model.

Table 5 shows an example calculation, for the above steps, of BMPs being implemented on hi-till, lo-till, and/or feedlot land use categories using the BMP module within HSPF. Within the Excel workbook, implementation levels are assigned for the BMPs that are applicable for each land use category (as shown in Table 3). These BMPs are assumed to be applied in parallel, i.e. independent of each other; thus, a single ‘effective’ BMP for each land use category using area-weighted constituent specific REs can effectively represent the suite of BMPs and implementation levels assigned. In Table 5, the example results of STEP 2 show the ‘effective’ REs that would be transferred to the BMP module for implementation levels shown in STEP 1.

The connectivity of watershed areas, receiving water bodies and reaches, and BMPs is established within the SCHEMATIC block of the HSPF UCI file. The SCHEMATIC block is created within the Excel file to appropriately establish this connectivity based on the implementation level prescribed for each new scenario. Since we are using ‘effective’ area-weighted BMP REs, the entire area served for a land use category is routed to a single BMP module operation in HSPF where the effective REs are then applied. For example, based on the previous tables we would route 70% of the hi-till acres to the hi-till composite BMP, reduce the constituent loadings from these acres by the calculated effective REs listed in STEP 2, and then transfer any remaining loads to the downstream reach or water body.

Table 5 – Example Scenario Calculation with Multiple BMPs Implemented

[HT – Hi-Till, LT – Lo-Till, F - Feedlot]

STEP 1: Assign Implementation Levels for Example Scenario

		BMPs in Parallel		
	BMP Strategies	*HT*	*LT*	*F*
1	Riparian/Ditch Buffers	0	0	
2	Wetland Restoration	0	0	
3	Ag BMPs/Crop Residue Management	10	10	
4	Feedlot Upgrades			10
5	Comprehensive Nutrient Management	0	0	
6	Ag BMPs/Crop Residue Management + Comprehensive Nutrient Management	60	60	
	% of Area Served	70	70	10

STEP 2: Calculate Effective REs for the Scenario with the defined Implementation Levels and BMPs (above)

BMP	TSS	BOD	NH3	NO3	ORG N	PO4	ORG P	ORG C
3	75	40	40	35	60	45	70	50
4	65	25	35	10	40	30	50	40
6	75	64	64	68	72	67	79	55

Resulting 'effective' Area-Weighted BMP REs for the Scenario

BMP	TSS			BOD			NH3			NO3			ORG N			PO4			ORG P			ORG C		
	HT	*LT*	*F*	*HT*	*LT*	*F*	*HT*	*LT*	*F*	*HT*	*LT*	*F*	*HT*	*LT*	*F*	*HT*	*LT*	*F*	*HT*	*LT*	*F*	*HT*	*LT*	*F*
Effective	75	75	65	61	61	25	61	61	35	63	63	10	70	70	40	64	64	30	78	78	50	54	54	40

STEP 3: Revise HSPF UCI Areas to Establish the BMP and non-BMP Connectivity (see discussion below)

Special Issues for Tile Drains and Bank/Bluff Erosion

Tile drains and bank and bluff erosion contribute significant sediment and sediment associated contaminant loadings to water bodies and reaches in the watershed. Within the model, these sources are modeled using the HSPF SPECIAL ACTIONS capability, and input into the water bodies as a direct source. Representing surface tile buffers and stream bank stabilization is accomplished by using a reduction, or multiplication factor, for each constituent on the base condition loadings. The factor represents the combined impact of both the RE and the implementation level of the BMP. A similar approach can be used to reduce point source loads in the model, where a reduction factor is applied directly to the base condition loading.

Scenario Output and Summaries

For each alternative scenario run, a report is produced by the HSPF REPORT module to summarize the loads removed by the BMPs and the resulting loads received by the water bodies. This report is imported into another Excel workbook where the load per acre, total load, and percent of load by source are calculated. The workbook also allows for different scenarios to be compared to the base or other alternative scenarios.

Each run also stores a time series of the instream loads and concentrations at the watershed outlet. Using GenScn, these alternative scenarios can be readily compared/analyzed using a suite of graphical and statistical comparisons. By gaining an understanding of how the watershed and instream loads are changing from scenario to scenario using this process, the effectiveness of the BMPs and prescribed implementation levels assigned can be determined.

MODEL MANAGEMENT SCENARIOS

To assess the level of effort that would be necessary to achieve target values of the response variable chlorophyll *a* in the Blue Earth River, modified HSPF models of the watershed were constructed using various assumptions about percent implementation of the above listed BMPs. Multiple-year simulations of these "scenarios" (Table 6) were run in HSPF and used to drive six-year AQUATOX simulations, so that the potential impact of management measures on long-term average chlorophyll *a* in the Blue Earth River could be assessed. The six-year simulation period (1995-2000) was selected for this portion of the exercise because chlorophyll *a* concentrations were generally higher during this part of the baseline AQUATOX simulation than during the earlier modeled period (1990-1994). This helps to ensure a degree of conservatism in the results, which are shown in Table 7 and displayed graphically in Figure 17. The scenario A baseline condition represents an approximation of current (year 2000) conditions on the watershed.

Table 6. Mitigation scenarios modeled for the Blue Earth River watershed.

	Percent Implementation:					
Scenario	Riparian/Ditch Buffers	Wetland Restoration	Ag BMPs/Crop Res. Mgt/ Comprehensive Nut. Mgt.	Feedlot upgrades	Streambank Stabilization	Surface Tile Buffers
A*	0	0	0	0	0	0
B	10	10	10	10	0	0
C	10	10	10	10	10	10
D	20	20	20	10	0	0
E	20	20	20	10	10	30
F	30	30	40	10	10	30
G	0	0	100	10	10	30

* reflects current conditions

Table 7. Model results for Blue Earth mitigation scenarios (six-year simulations).

Scenario	mean TP (mg/L)	mean TSS (mg/L)	mean NO_3^- (mg/L)	mean chl_*a* (ug/L)	green algae (mg/L)	blue-green algae (mg/L)	ratio blue-green to green
A	0.268	77.1	8.35	18.6	0.00101	0.846	835
B	0.255	71.5	7.06	21.4	0.00122	0.903	743
C	0.254	68.8	7.06	21.2	0.00122	0.878	717
D	0.242	65.9	5.75	16.7	0.00120	0.504	419
E	0.242	57.7	5.75	15.3	0.00123	0.500	406
F	0.224	49.7	3.90	14.4	0.00121	0.104	86.3
G	0.213	49.2	3.07	12.2	0.00119	0.031	26.0

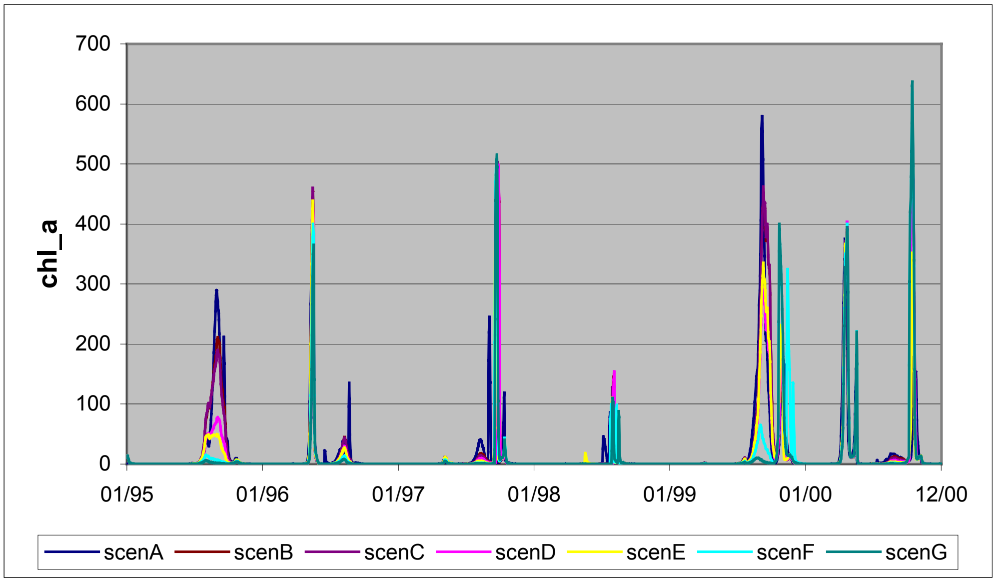

Figure 17. Results of six-year chlorophyll *a* simulations for current conditions (scenA) and various mitigation scenarios.

The six-year mean chlorophyll *a* concentrations in all of the modeled mitigation scenarios are above the hypothetical response variable criteria developed under both methods. Under current conditions (scenario A), annual mean chlorophyll *a* concentrations exceed the method 1 criterion (7.85 : g/L) in four out of six modeled years, and the method 2 criterion (7.5 : g/L) in five out of six years. Under the most stringent mitigation scenario (scenario G) the annual exceedences drop only slightly, to three and four years out of six, respectively.

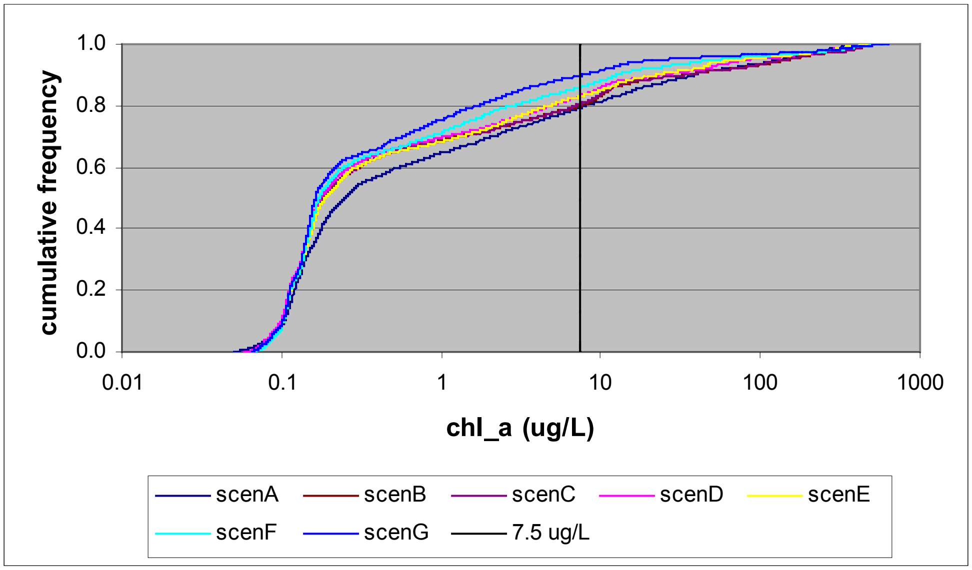

Figure 18. Cumulative distributions of daily mean chlorophyll *a* from six-year simulations.

Although neither of the hypothetical criteria are achieved under any of the mitigation scenarios, a substantial decrease in mean chlorophyll *a*, and corresponding decrease in the ratio of blue-green to green phytoplankton concentrations as compared to current conditions, are nevertheless predicted to be achievable with heavy implementation of agricultural BMPs and management measures. Scenario G predicts a 34.4 percent decrease in mean chlorophyll *a* concentration in response to a simultaneous decrease of 20.5, 36.2, and 63.2 percent in TP, TSS, and NO_3^-, respectively. Similarly disproportionate decreases in chlorophyll *a* in response to decreases in TP are predicted under other mitigation scenarios, suggesting that ecoregion-based nutrient stressor variable criteria might not necessarily need to be met in order for the corresponding response variable criteria to be attained.

DISCUSSION

Interpreting numeric water quality criteria as representing long-term mean target concentrations, these modeling results suggest that the hypothetical chlorophyll *a* criteria developed in this exercise may be difficult to achieve even under intense levels of BMP and management measure implementation. Even if modeling results had suggested a more dramatic decrease in chlorophyll *a*, it should be noted that years of historical nutrient enrichment in the Blue Earth system might serve to retard any such response to actual decreases in nutrient loads.

This exercise has focused only on BMPs and management measures implemented in parallel, that is no more than one category of BMP or measure is assumed to be implemented on any given land segment. Multiple BMPs/measures implemented on the same parcel of land would undoubtedly decrease nutrient and sediment export from that piece of land even further, though it is unclear how best to develop composite reduction factors for such a case. Nevertheless the scenarios in this exercise represent intense levels of implementation. For example, scenarios F and G represent 100 percent implementation within the watershed (*i.e.* runoff from every acre of crop land is assumed to be treated by either riparian/ditch buffers, restored wetlands, or the combined use of miscellaneous agricultural BMPs, crop residue management, and comprehensive nutrient management).

Use of simulations such as these, which mechanistically link water quality stressor and response variables to practices within the watershed, appears to offer the possibility of simultaneously addressing multiple programmatic water quality questions, including development of nutrient water quality criteria and assessing the question of designated use attainability. Once developed for such purposes, such models can also be adapted to develop Total Maximum Daily Loads (TMDLs) for the water bodies in question. The ability to simultaneously derive water quality criteria, develop TMDLs, and conduct Use Attainabilty Analyses (UAA) for nutrients in water bodies offers States substantial potential resource savings.

The analysis demonstrated in this exercise offers users a way to develop nutrient water quality criteria using relatively modest amounts of water quality monitoring data. This kind of approach can be used by itself, or in conjunction with other approaches such as regression-based analyses. Rather than modeling every water body in their territory, States and Tribes may choose to apply criteria developed based upon such a reach-specific analysis to all water bodies that are deemed to be sufficiently similar to the reach in question. Such a decision may be based upon results of water body vulnerability classifications such as those developed by Detenbeck *et al.* (2003), as well as related cluster analyses currently being developed by EPA's Office of Research and Development to assess the vulnerability of watersheds of various sizes in EPA's Region 5, which includes Minnesota.

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