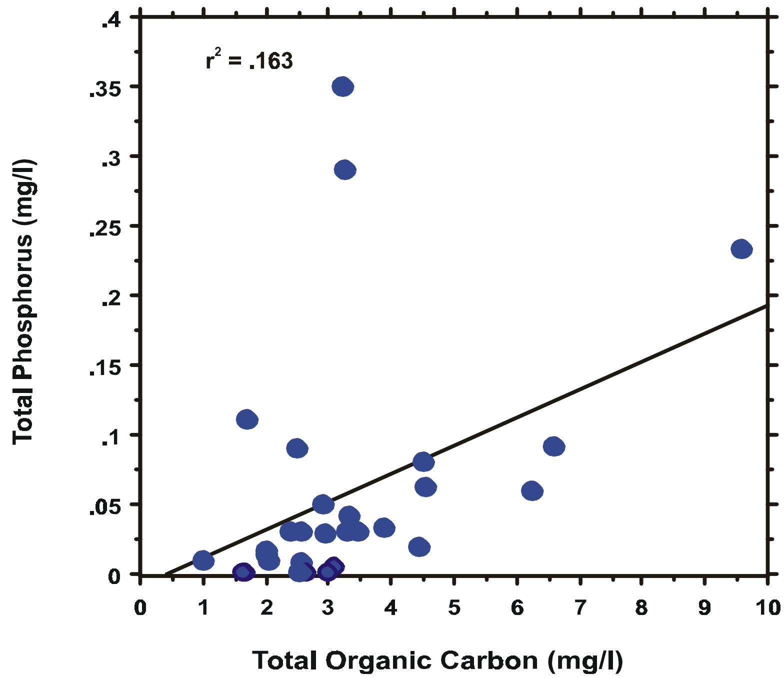

Figure A-5. Relationship between total phosphorus and TOC (r^2 value = 0.163) in ecoregion 67g.

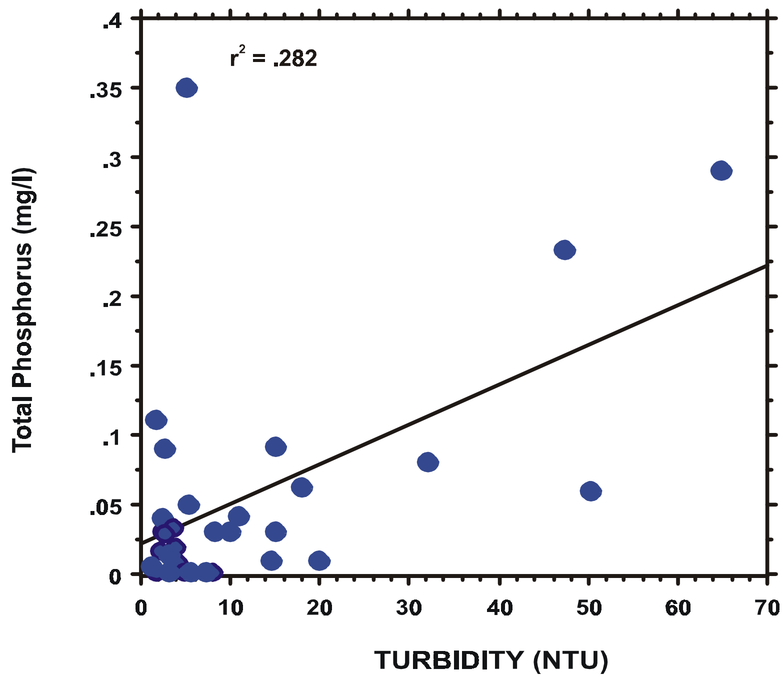

Figure A-6. Relationship between total phosphorus and turbidity (r^2 value = 0.282) in ecoregion 67g.

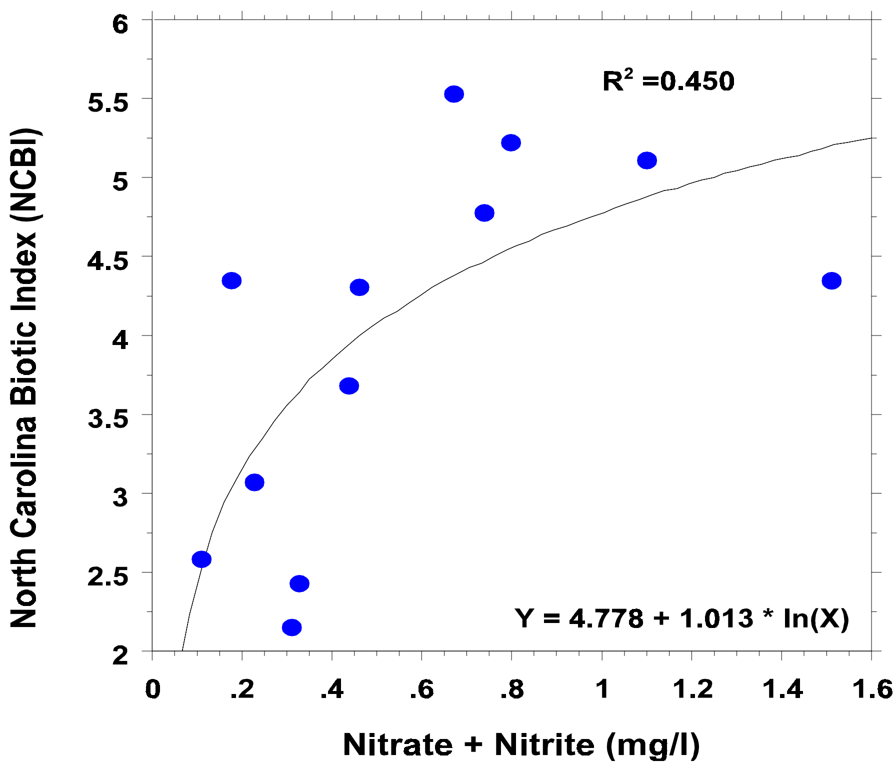

Figure A-7. Relationship between nitrate-nitrite levels and the Hilsenhoff Biotic Index.

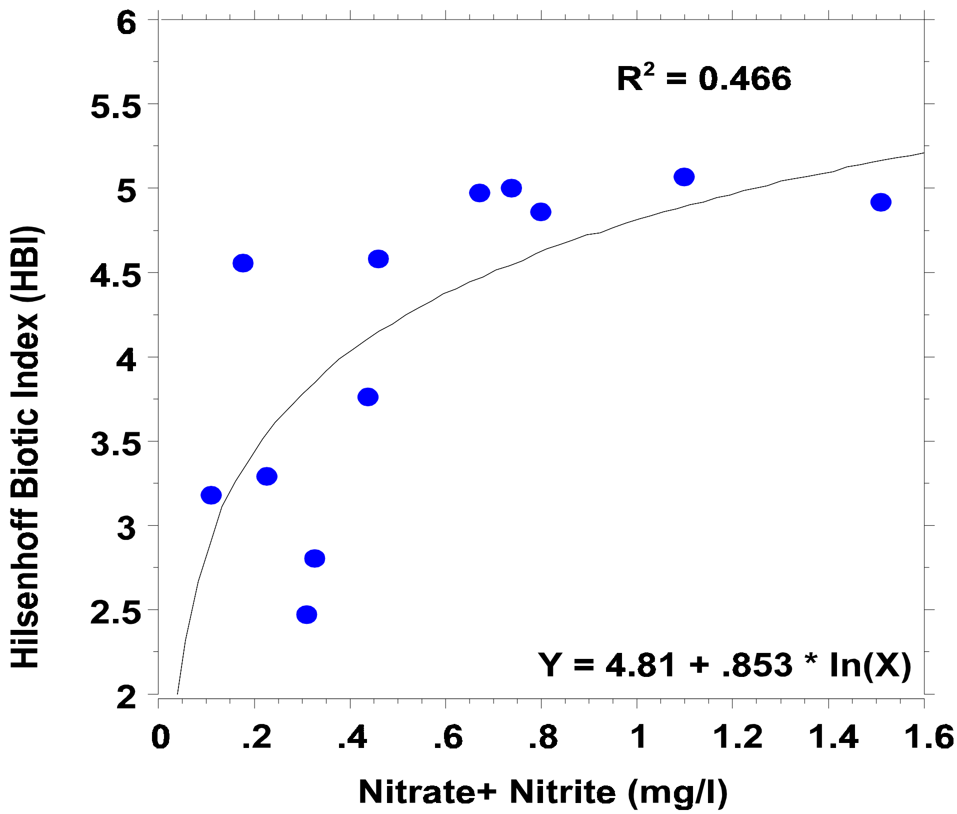

Figure A-8. Relationship between nitrate-nitrite levels and the North Carolina Biotic Index (NCBI).

While the two values, 1.2 and 1.0 mg/L, are not exactly the same, clearly these two methods of criteria development can be used to strengthen the rationale for a final criteria recommendation or to justify a "margin of safety". It also demonstrates that should the Division set the nitrate+nitrite goal for 71h at 1.0 mg/L, that level should generally be protective of biological integrity.

3. Another potential methodology for nutrient criteria development was examined. According to EPA draft guidance, the reference conditions may be compared to all other nutrient data to potentially provide a range for criteria selection. EPA suggests that the range is established by comparing the reference stream data at the 75th percentile with the 25th percentile of all other data. We were curious to see if this approach would work and if so, would it provide values similar to those we had already identified.

   To assist in this effort, EPA provided us with the nutrient databases from STORET for the three large nutrient regions in Tennessee. (For purposes of this initial test, only Tennessee STORET data were included.) Nutrient Region XI in east Tennessee is a combination of Level III ecoregions 66, 67, 68, and 69. Nutrient Ecoregion IX in middle Tennessee is composed of Ecoregions 71, 65, and 74. Ecoregion 73 in west Tennessee is Nutrient Ecoregion X.

   The EPA nutrient database was primarily data collected by the Division of Water Pollution Control, the Tennessee Valley Authority (TVA), and the U.S. Geological Survey (USGS). As we were familiar with TVA's monitoring program, we were concerned that some percentage of their data was from lakes or embayments. Since we were developing stream nutrient criteria, rather than lake or embayment criteria, we did not consider it appropriate to include non-stream data. Lacking the time to identify and cull only the embayment or lakes data from the database, we decided to exclude all TVA data.

   Figure A-9 illustrates a comparison of the National nutrient database for Nutrient Ecoregion Region XI and the reference stream database for the same geographic area. The 75th percentile of the reference stream data and the 25th percentile of the National Nutrient database lined up well for some ecoregions (68, 69, & 66), but not for the Central Appalachian Ridge and Valley Region (67).

   We also looked at EPA draft Nutrient Aggregate Ecoregion IX in West Tennessee (Figure A-10). Data for total phosphorus were elevated nearly an order of magnitude higher than the reference stream data. We discovered that a few stations provided a sizable number of data points within the database. It is possible that some of these data represent "storm chasing" sampling events designed to quantify worst case nutrient loadings. Another possibility is that sampling in the phosphorus-rich soils of ecoregion 71 biased the database. If we can identify these sites and determine that these data are not representative of the ambient water quality in the ecoregion, these data could be excluded and the database re-formed.

SUMMARY

With the assistance of EPA, the Tennessee Division of Water Pollution Control subdelineated ecoregions from Level III to Level IV. Reference streams were identified in each sub-ecoregion to establish a

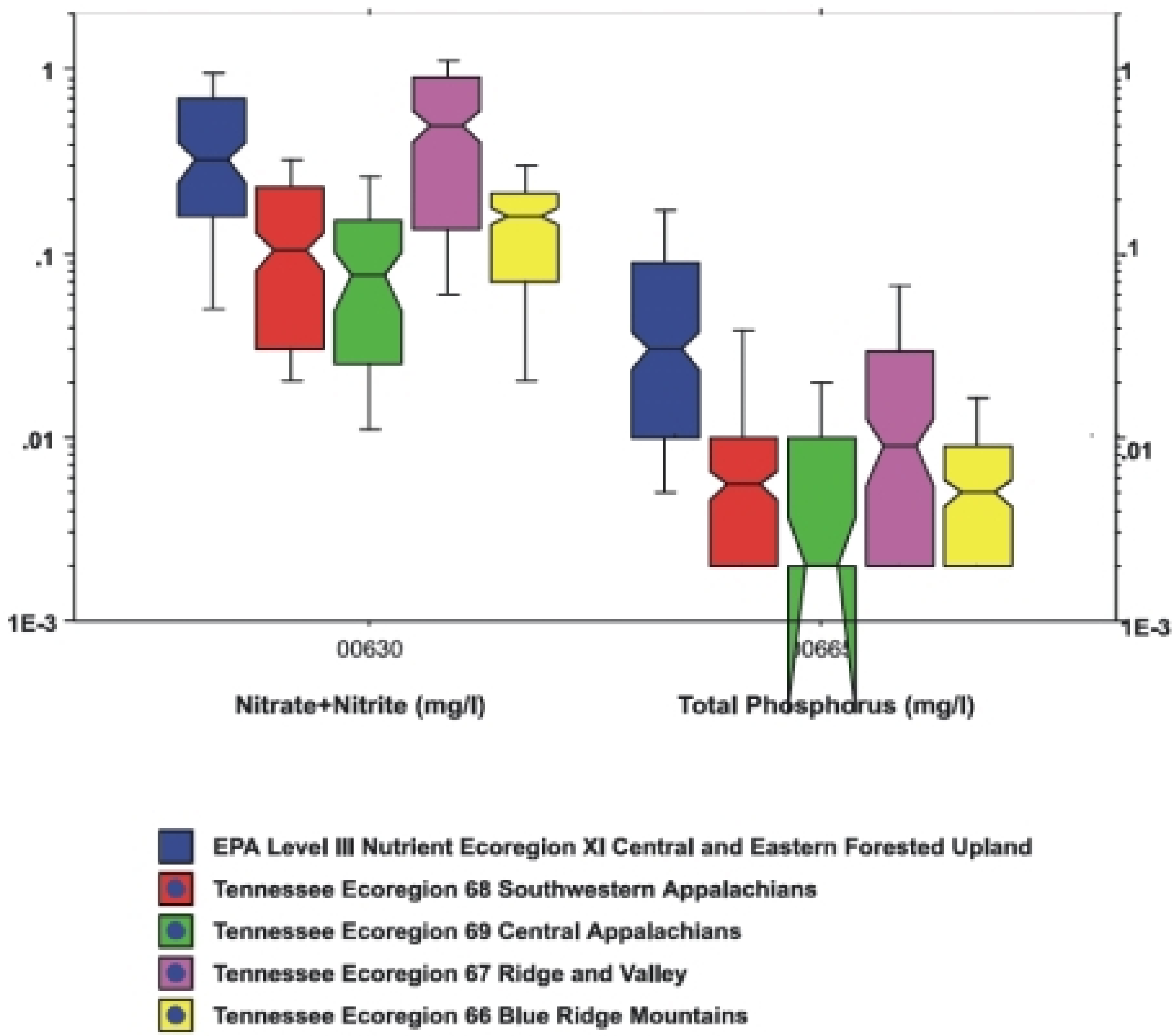

Figure A-9. Comparison of EPA Nutrient Ecoregion Region XI data to the Tennessee reference stream database for the same geographic area.

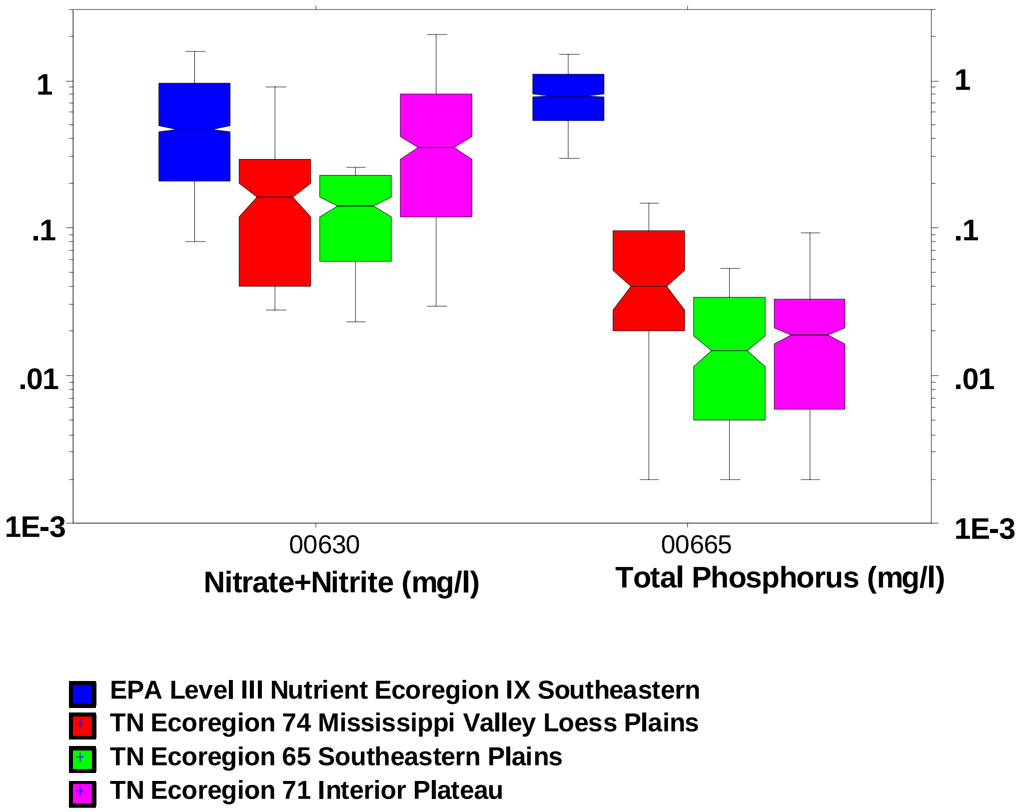

Figure A-10. Comparison of EPA Nutrient Ecoregion Region IX data to the Tennessee reference stream database for the same geographic area.

database of least-impacted conditions. These databases will be used to develop nutrient criteria based on either the 75th or 90th percentile of the data.

Attempts to identify a relationship between nutrient levels and other parameters such as turbidity, TOC, and suspended solids were confounded by the amount of data below the detection level. While data relationships were indicated, they were not strong. Further investigations might include similar comparisons using the national nutrient database values.

Relationships between nutrient data and biological indices were explored to see if positive correlations could be established. Such correlations could be used to strengthen a criteria justification and to insure that potential criteria values will be protective of biological integrity. The preliminary results are promising.

Tennessee's reference stream data were also compared to values from the national nutrient database. In several ecoregions, the 75th percentile of the reference data corresponded well with the 25th percentile of the national database. However, certain ecoregions did not correspond well, possibly suggesting that there are distinct differences within the EPA nutrient ecoregions. States would be well advised to consider these differences in setting nutrient goals.

Additionally, states should examine the national nutrient database carefully and use local knowledge to identify stormwater or embayment stations. Data from specific event sampling and reservoir or embayment stations may not be representative of the ambient water quality in the region. Such data could inappropriately bias results.

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CLARK FORK RIVER—SCIENTIFIC BASIS OF A NUTRIENT TMDL FOR A RIVER OF THE NORTHERN ROCKIES[1]

V.J. Watson,[2] Gary Ingman,[3] and Bruce Anderson[4]

ABSTRACT: In recent decades, river bottom algal levels have interfered with beneficial uses of western Montana's Clark Fork of the Columbia. The total maximum daily load analysis (TMDL) required by the Clean Water Act was addressed through a voluntary nutrient reduction plan developed by a stakeholder group with the aid of scientists. Targets for acceptable nutrient and algal levels were set using modifications of established criteria, literature values, and levels observed in the Clark Fork where algae problems did and did not occur. These targets were considered starting points that would be refined as more long-term data on the Clark Fork become available. Nutrient load reductions needed to meet instream targets were estimated using a model that diluted loads in the 30 day 10 year low flows. It appeared possible to achieve instream targets in most of the river with reductions that the main dischargers considered reasonably achievable, if other small dischargers and nonpoint sources were also controlled. Hence 4 local governments and one large industry signed the VNRP, and a VNRP coordinator was hired to obtain the participation of other sources.

KEY TERMS: nutrients, TMDL, benthic algae, benthic chlorophyll

INTRODUCTION

River bottom algal levels were first recognized as a water quality problem in the Clark Fork River of western Montana in the 1970's when it was found to lower dissolved oxygen levels below state standards on warm summer nights (Braico 1973). Massive algae growths and low oxygen levels were noted through the low flow summers of the 1980's (Watson 1989a; Watson and Gestring 1996) and identified as a critical problem by the Montana governor's office (Johnson and Schmidt 1988). In 1987, the reauthorization of the Clean Water Act called for a study and action plan to address nutrients and associated nuisance growths in the Clark Fork basin from Montana to Washington. The act also established the Tristate Implementation Council to carry out the study and plan. The resulting study (USEPA 1993b) documented that nuisance levels of algae were interfering with beneficial uses in 250 miles of river in Montana. The Council convened a group of stakeholders (dischargers, local governments, and conservation groups) which spent 4 years developing a voluntary nutrient reduction plan or VNRP to restore the river's integrity. The plan was signed in August, 1998, and EPA accepted the VNRP as a TMDL because it had a rational, scientific basis and provided a margin of safety. The VNRP will continue to serve as a TMDL as long as reasonable progress is shown toward its goals.

Unlike a TMDL, the VNRP did not require that effluent limits be written into permits, rather permits simply reference the VNRP which states the instream targets for algae and nutrient levels and timetables

[1] This paper was published previously and is used with permission of the publisher. Olsen, D. S. and J. P. Potyondy (Eds.). 1999. *Wildland Hydrology*. American Water Resources Association. Herndon, VA. TPS-99-3. 536 pp.
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to achieve these, suggests likely loading reductions needed to achieve these, and lists some methods signatories agree to pursue to achieve reductions. By signing the VNRP, stakeholders agree to implement certain efforts to achieve loading reductions, to monitor and evaluate results and to pursue additional efforts if needed to reach targets. The VNRP also recognizes that the targets and reductions pursued are based on the best information currently available and are subject to renegotiation as more information becomes available. The VNRP references a long-term monitoring plan aimed at gathering more information and evaluating the effect of load reduction efforts. The VNRP also explains the scientific basis for the targets, load reductions, monitoring plan, margin of safety and areas of uncertainty. This paper discusses the scientific basis of the VNRP by addressing a series of questions.

QUESTIONS ADDRESSED BY THE VNRP

What Are Current and Desired Algae Levels in the River?

Summer algal levels in the Clark Fork vary dramatically in time and space, from highs of over 500 mg of chlorophyll a/sq. m. in the upper river in the 1980's to lows of 3 mg/sq. m. at some sites in recent years (Watson and Gestring 1996; Watson unpublished data).

Currently, EPA is developing guidance to assist states in developing nutrient and algal criteria. It is likely that this guidance will direct the states to develop criteria based on little-impacted reference water bodies in each ecoregion. The Clark Fork VNRP committee found little guidance in the literature on what algal levels were natural to this region or what levels were associated with water quality problems.

The British Columbia Ministry of the Environment considers that recreation and aesthetics are protected when algal levels are below 50 mg chlorophyll a/sq. m. and that undesirable changes in aquatic life will be avoided at levels below 100 mg/sq. m. (Nordin 1985). Although these criteria were developed for small, shallow streams, Nordin agrees that it is reasonable to apply them to the shallow parts of large rivers (Nordin pers. comm.). Welch et al. (1988) demonstrated that filamentous algae tend to dominate stream communities when chlorophyll levels exceed 100 mg/sq. m. and proposed that nuisance levels exist above 100-150 mg/sq. m. The VNRP committee decided to adopt these target algal levels: less than 100 mg chlorophyll a/sq. m. when averaged over the growing season and 150 mg/sq. m. as the maximum acceptable peak.

The committee agreed that these algal targets might be revised in time as more information becomes available concerning what levels appear associated with water quality problems. In the mid 1980's, river algal levels contributed to violations of the state dissolved oxygen standard. However, that standard has since been raised and is no longer exceeded, changing this view of what constitutes nuisance levels. But it was recently discovered that river algae lower dissolved oxygen and pH sufficiently on summer nights to release toxic heavy metals from old mine wastes in the river bed, violating water quality standards. Further studies are needed to determine what algal levels would avoid this and other water quality problems.

What Actions Seem Most Likely to Reduce Algal Levels?

Many factors affect river algal levels, including scouring, shading, grazing, toxic chemicals and available nutrients. The VNRP committee agreed that the factor that can best be managed to reduce algal levels in the Clark Fork is available nutrients.

How Much Must Nutrients Be Reduced to Achieve Algal Targets?

This question raised many others. What form of nutrients should be assessed, total or soluble? Which nutrient is most limiting, nitrogen or phosphorus? At what levels do nutrients become limiting? Should we focus on nutrient levels or loads?

Based on N:P ratios in the river, Watson (1989b) found that both N and P appear to be limiting at some times in some river reaches. Hence, the committee concluded that both nutrients should be reduced if possible. Artificial stream studies by Bothwell (1989) and Watson (1989) indicated what levels of soluble nutrients are low enough to reduce algal levels in artificial streams. However, using a 200 river database, Dodds et al. (1997) pointed out that total nutrient levels are better correlated with algal levels than are soluble nutrient levels. So the VNRP committee opted to focus on total nutrients (while monitoring soluble nutrients to insure they did not rise). A variety of approaches suggested targets ranging from 250-350 total N and 20-45 total P, so the committee adopted 300 ppb total N and 39 ppb total P in the middle river and 20 ppb total P in the upper river (where a higher N:P ratio was desired to discouraged the filamentous alga *Cladophora*).

What Are Major Nutrient Sources and How Much Reduction Is Needed?

The basin wide study called for in the 1987 Clean Water Act bill found that both point and nonpoint sources accounted for significant portions of nutrient loading, hence both must be reduced (USEPA 1993b). However, the largest sources were found to be three municipal discharges (Butte, Deer Lodge and Missoula), a pulp mill and a county (Missoula) with large areas of unsewered development. Hence these 4 local governments and one private industry were initial signatories to the VNRP. Ultimately, the VNRP committee hopes to convince smaller point sources and nonpoint sources (other developing counties and large landowners) to agree to certain efforts to control nutrients and to sign the VNRP.

To estimate the amount of load reductions needed, the Montana Department of Environmental Quality (DEQ) modified a model provided by EPA that estimates instream concentrations from loads, flows and historic percent losses within each river reach. This model allowed DEQ to estimate how much loads would need to be reduced from various sources to meet instream targets. Once again, the committee recognized that this simple model did not include all the gains and losses and so provided only a rough estimation of likely concentrations resulting from given loads. The model predicted that reductions the committee felt were reasonably possible would achieve instream targets in almost all the impaired reaches. The model suggested reaching targets in the few remaining miles of river would require reductions of questionable feasibility. The committee agreed to use the model only as a general guide and not to set required reductions. It was pointed out that algal uptake might reduce nutrient levels lower than the model predicted.

How Was a Margin of Safety Incorporated in the VNRP?

A margin of safety is provided by using instream nitrogen targets that are more protective than those recommended by Dodds et al. (1997). In addition, needed load reductions were estimated using the river's dilution capacity at very low flows—the 30 day 10 year low flow (the lowest 30 day average flow likely to be observed in one of 10 summers). Hence, targets will likely be met in almost all the river, in all but one month out of 10 years.

What Actions Are Expected to Achieve Needed Load Reductions?

All the municipalities in the area have adopted a phosphate detergent ban which has reduced P loads. The city of Deer Lodge agreed to land apply its wastewater. The city of Butte agreed to augment stream flows and pursue various land application options. The city of Missoula has reduced nutrient loading by operating its activated sludge plant like a biological nutrient removal plant. It also plans to construct a biological nutrient removal plant or use a combination of wetland treatment and land application in the future. The pulp mill will reduce summer discharge, store its water so as to reduce seepage, and increase use of a color removal process that also reduces nutrients. Missoula County will reduce and control loading from septic systems through land use planning and controls.

The VNRP committee has hired a VNRP coordinator to work with small discharges, local governments and land owners to identify ways these can reduce or at least control nutrient loads. These efforts are needed to avoid losing ground given the rapid population growth occurring in the area.

How Will Progress Towards the Targets Be Determined?

The TriState Implementation Council contracted with Land & Water, Inc., to develop and carry out a long term monitoring plan (Land & Water 1996) that will provide reliable information on nutrient related water quality status and trends in the basin. The monitoring plan uses a statistically rigorous sampling scheme designed to be able to detect trends in algal and nutrient levels in the Clark Fork and to assess compliance with instream targets. Using a seasonal Kendall with Sen slope estimate, the monitoring plan is intended to be able to detect a 50% change in nutrient levels over a 10 year period with 95% confidence and 90% power. In addition it can detect a 35% change in algal levels over a 10 year period with 90% confidence and 80% power. Compliance with instream targets will be evaluated annually using excursion analysis.

Monitoring consists of sampling 32 stations on the mainstem and major tributaries for total and soluble nutrients monthly (with biweekly sampling in summer). Algal levels are sampled at 7 mainstem stations twice a summer. Because of the high spatial variability in algal distributions, 10-20 replicates are collected. Details of the algal sampling scheme appear in Watson and Gestring (1996).

Timelines in the VNRP focus on timing of actions. However, the goal of the VNRP is to reduce algal level to the point that beneficial uses are fully supported by the end of the 10 year plan. Hence, the plan should be regarded as successful if a significant downward trend in nutrient and algal levels is detected 5 years into the plan, and if targets are no longer exceeded by the end of the 10 year plan. Of course, it will be necessary to evaluate changes in these parameters in light of the flows observed over this 10 year period.

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UPPER MIDWEST RIVER SYSTEMS—ALGAL AND NUTRIENT CONDITIONS IN STREAMS AND RIVERS IN THE UPPER MIDWEST REGION DURING SEASONAL LOW-FLOW CONDITIONS

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INTRODUCTION

Extensive agricultural practices in the Midwestern Corn Belt region over the past 100 years have contributed to nonpoint source degradation of water quality and biological integrity in many streams and rivers. For example, intensive row-crop production and confined animal-feeding operations in Iowa, Illinois, and southern Minnesota have resulted in accelerated nutrient and organic enrichment in tributary streams, as well as in the Mississippi River (Goolsby et al. 1991; Coupe et al. 1995) and the Gulf of Mexico (Turner and Rabalais 1994; Rabalais et al. 1996). When ambient light and other algal-growth factors are favorable, nutrient enrichment can promote excessive productivity and respiration in streams and rivers, resulting in aesthetic and recreational impairments, departures from water quality criteria, and adverse effects to aquatic life. The U.S. Environmental Protection Agency (USEPA) has been charged with developing guidance for establishing regional water quality criteria to protect streams and rivers from accelerated eutrophication processes (http://www.cleanwater.gov). Results from State water quality (305[b]) reports to Congress indicate that over 40% of streams and rivers in the U.S. are contaminated by nutrient runoff and resultant indicators of excessive algal productivity.

Despite the prevalence of eutrophication, no implicit standards or criteria have been proposed to protect beneficial water uses (e.g., no significant ecological changes) in streams and rivers, apart from drinking-water standards for nitrate and chronic aquatic life criteria for elemental phosphorus in estuarine/marine waters. Although predictive algal-nutrient relations have been established for classifying the trophic status of lakes and reservoirs (Carlson 1977; Reckhow and Chapra 1983), there is no generally accepted system for classifying streams and rivers (Dodds et al. 1998; Dodds and Welch 2000). Recent approaches for classifying algal-nutrient relations in lotic systems have focused on constructing frequency distributions of total nutrients and periphyton (Biggs 1996; Dodds et al. 1998) or seston (suspended algae or phytoplankton) (Van Niewenhuyse and Jones 1996), and establishing boundaries between oligotrophic–mesotrophic and mesotrophic-eutrophic conditions, similar to trophic criteria established for lakes. Results from these investigations have suggested criteria for total nitrogen (TN>1500 μg/L), total phosphorus (TP>75 μg/L), seston chlorophyll *a* (chl *a*>30 μg/L), and periphyton (chl *a*>100-200 mg/m^2) to avoid adverse effects of stream eutrophication. Periphyton results from these and other such studies (Welch et al. 1988; Biggs and Close 1989; Lohman et al. 1992; Watson and Gestring 1996; Dodds et al. 1997) are representative of streams with gravel or rock substrates that were characterized by nuisance growths of filamentous green algae. Relatively little is known about nutrient and algal-productivity relations in low-gradient streams with unstable, sand, or silt bottoms. Even less is known about natural and human factors that contribute to the predominance of seston or periphyton in streams, relations with landscape factors such as agricultural intensity and riparian zones, and how differences in algal-nutrient relations influence stream metabolism and biological integrity.

To provide better understanding of eutrophication conditions and processes in streams and rivers in the upper Midwest Corn Belt region, the USGS National Water-Quality Assessment (NAWQA) Program conducted a large water quality study in the Minnesota, Wapsipinicon, Cedar, Iowa, Skunk, and Illinois River basins during seasonal low-flow conditions in August 1997. The study was a cooperative effort among three NAWQA projects: the Upper Mississippi River basin, Eastern Iowa basins, and Lower Illinois River basin study units. The objective of the study was to evaluate algal and macroinvertebrate responses to nutrient, herbicide, and organic enrichment from nonpoint agricultural sources relative to natural factors such as riparian vegetation, soil-drainage characteristics, and hydrology. This paper summarizes the status of algal and nutrient conditions in portions of the Central and Western Corn Belt Plains ecoregions (Omernik 1986), which could serve as a starting point for USEPA and State/Tribal agencies to establish regional nutrient criteria in rivers and streams in relation to low-flow conditions.

METHODS

Water chemistry and biological samples were collected from 70 streams and rivers in southern Minnesota, eastern Iowa, and western Illinois during seasonal low-flow conditions in August 1997. The study area is one of the most intensive and productive agricultural regions in the world; average row-crop production of corn and soybeans in stream watersheds accounts for over 90 percent of land cover (Sorenson et al. 1999). The density of riparian vegetation was quantified at two spatial scales: stream reach and segment. The length of a stream reach was approximately 20 times the mean wetted channel width (Fitzpatrick et al. 1998). The length of a stream segment was defined as the $\log_{10}$ of the basin area upstream from each sampling location, ranging from approximately 3 km to 4.9 km. Basin soil-drainage characteristics were quantified using information from the U.S. Soil Conservation Service STATSGO database. Water chemistry samples were collected for total and dissolved nutrients, dissolved herbicides and metabolites, and suspended and dissolved organic carbon (Shelton 1994). Stream productivity and respiration were estimated from continuous measurements of dissolved oxygen (DO) concentrations and pH over a 48-hour period. Phytoplankton (algal seston) samples were collected in conjunction with water-chemistry sampling, and quantitative samples of periphyton (benthic algae) and macroinvertebrates were collected from submerged woody debris. Water clarity was quantified using a light meter and submersible quantum sensor; the depth of the euphotic zone was measured or estimated by comparing subsurface photosynthetically-active radiation (PAR) with PAR measurements at the bottom of the deepest pool in the stream reach. Stream flow and velocity were measured using standard USGS procedures. Land-use and cover information was determined for each basin using ARC-INFO GIS procedures with the most-recent (1996-97) agricultural data that were available. A summary of the study design and methods, and data discussed in this report is presented by Sorenson et al. (1999; http://wwwrcolka.cr.usgs.gov/nawqa).

NUTRIENT INDICATORS OF TROPHIC CONDITION

Nutrient concentrations in many streams in the upper Midwest region are relatively higher than in other areas of the country, exceeding criteria proposed generally for temperate streams and rivers. For example, median concentrations of total nitrogen (TN; NH_4+NO_2+NO_3+organic N) and total phosphorus (TP; dissolved orthophosphate + particulate phosphorus) (Table A-1) exceeded the mesotrophic-eutrophic boundaries of 1500 μg/L (TN) and 75 μg/L (TP) proposed for temperate streams (Dodds et al. 1998). Average stream concentrations of dissolved nitrite+nitrate nitrogen (NO_2+NO_3-N) and total organic nitrogen (TON) were significantly ($p<0.05$) higher in the Minnesota River basin; nitrate concentrations exceeded 8 mg/L in nearly one third of these streams. Although concentrations and annual loads of TN increase with the intensity of nitrogen sources (e.g., fertilizer application and other land-use practices) nationally (Fuhrer et al. 1999), concentrations in Midwestern streams during seasonal, low-flow conditions were not related to rates of fertilizer application or the number of livestock in agricultural watersheds. Instead, NO_2+NO_3-N concentrations increased significantly with stream flow, corresponding with differences in rainfall and runoff in the region during the months prior to the study, and TON concentrations were correlated with the abundance of phytoplankton (seston), as indicated by chl *a* concentrations. Concentrations of NO_2+NO_3-N decreased significantly with increases in seston chl *a* concentrations. Particulate phosphorus (total phosphorus as P; Table A-1) concentrations did not differ significantly relative to human or natural factors; however, concentrations of dissolved orthophosphate (DoP) varied in relation to the importance of ground-water discharge and the abundance of benthic algae (periphyton) in Midwestern streams and rivers. Dissolved orthophosphate (available directly for algal growth) accounted for about 28 percent of the concentration of TP.

NATURAL FACTORS THAT INFLUENCE NUTRIENT INDICATORS OF TROPHIC CONDITION

Soil drainage and landform characteristics in the upper Midwest region were influenced profoundly by patterns of glacial advance and retreat during the late Pleistocene era. For example, soils on the Wisconsin glacial lobe in north-central Iowa and southern Minnesota are characterized by fine-grained materials through which water drains very poorly, whereas soils in eastern Iowa and western Illinois contain relatively larger proportions of sand and coarser grained materials that constitute moderately-well drained soils. The proportion of stream water that is derived from ground-water inflow is substantially less in streams on the Wisconsin lobe than in streams located to the southeast of the Wisconsinan glacial advance (Winter et al. 1998). Land-surface runoff, via tile drains, is probably an important contributor to nutrient fluxes in streams that drain low-gradient, prairie-pothole landscapes. In contrast, ground-water inflow contributes appreciably to stream flow, particularly during low-flow periods, in areas with moderately-well drained soils such as the Wapsipinicon, Cedar, and Illinois River

Table A-1. Distribution of nutrient concentrations (in µg/L) in Midwestern agricultural streams and rivers.

Water quality constituent	10^{th} percentile	25^{th} percentile	50^{th} percentile (median)	75^{th} percentile	90^{th} percentile	Maximum value
Total Nitrogen[1]	948	1364	2627	4205	8550	13679
Total Phosphorus[2]	61	114	175	235	523	1092
Dissolved NH_4-N	<15	<15	17	46	105	1308
Dissolved NO_2+NO_3-N	103	278	1320	3415	8145	12730
Total Organic N	356	570	934	1258	1560	2899
Dissolved ortho-P	<10	19	41	72	161	409
Particulate Phosphorus[3]	39	68	139	185	378	778

[1] Sum of dissolved NH_4-N + dissolved NO_2+NO_3-N + total organic N
[2] Sum of dissolved ortho-PO_4 + particulate phosphorus
[3] Total phosphorus as P (USGS WATSTORE code 00665)

basins (Walton 1965; Heintz 1970; O'Hearn and Gibb 1980; Squillace et al. 1996). Figure A-11 shows soil-drainage relations among stream and river basins in the study (U.S. Soil Conservation Service STATSGO data normalized to watershed area; Sorenson et al. 1999) and the correspondence with the Wisconsinan glacial advance.

Concentrations of TN and TP varied in relation to soil-drainage and riparian-zone conditions in the upper Midwest region (Figure A-12). Average TN concentrations were significantly higher in stream basins with very-poorly drained soils, such as those in the Minnesota River basin. In basins with moderately-well drained soils, concentrations of TN were significantly lower in streams with well-developed riparian zones, suggesting that the presence of riparian trees may beneficially influence water quality conditions in streams with appreciable ground-water discharge. Average TP concentrations were relatively lower in streams with moderately- or poorly-drained basins and well-developed riparian zones (Figure A-12), but concentrations of TP did not differ significantly in relation to riparian conditions. Average TP concentrations were significantly less in streams with a low percentage of riparian trees and very-poorly drained basins; however, average TP concentrations were generally (but not significantly) lower in streams with well-developed riparian zones (Figure A-13).

Dissolved nutrient concentrations differed in relation to basin soil-drainage properties and riparian-zone conditions, but nutrient conditions were more related to algal abundance and productivity in streams and rivers than physical factors. Average concentrations of dissolved ammonia-nitrogen (NH_4-N) were significantly higher in streams that drain basins with moderately well-drained soils, whereas average dissolved NO_2+NO_3-N concentrations were significantly higher in streams with very-poorly drained soils, such as those on the Wisconsin lobe. Similarly, average DoP concentrations were relatively higher in highly-shaded streams with moderately well-drained basins, whereas concentrations of DoP were significantly lower in poorly-shaded, poorly-drained stream systems on the Wisconsin lobe. The combination of very-poorly drained soils, high rainfall and land-surface runoff relations, and extensive tile drainage in the Minnesota River basin may account for the higher-than-expected concentrations of TN and dissolved NO_2+NO_3-N concentrations in these streams. Relatively larger concentrations of NH_4-N and DoP in streams with moderately-well drained basins may indicate ground-water fluxes of these constituents that reflect both present and past agricultural intensity. The time of constituent transport along local and regional ground-water flow paths can range from months to years. Integration of these results could indicate an interaction among land-use practices, stream hydrology, riparian shading, and algal-nutrient relations.

ALGAL INDICATORS OF TROPHIC CONDITION

Algal indicators of eutrophication in streams and rivers of the upper Midwest region are related to agricultural intensity (fertilizer application and livestock in stream basins), soil-drainage conditions, hydrology, and riparian-zone conditions along stream segments. Median and inter-quartile seston chl *a* concentrations (Table A-2) are similar to those reported from mesotrophic-to-eutrophic lakes and reservoirs (e.g., Carlson 1977), and seston (but not periphyton) chl *a* concentrations were significantly higher in poorly-shaded than well-shaded streams (Figures A-13 and A-14). These results likely indicate that ambient light conditions influence the development of large phytoplankton populations in Midwestern streams and rivers. Seston chl *a* values indicative of eutrophic conditions (greater than 30 μg/L) were found in streams that drain basins with poor soil drainage, high rates of fertilizer application,

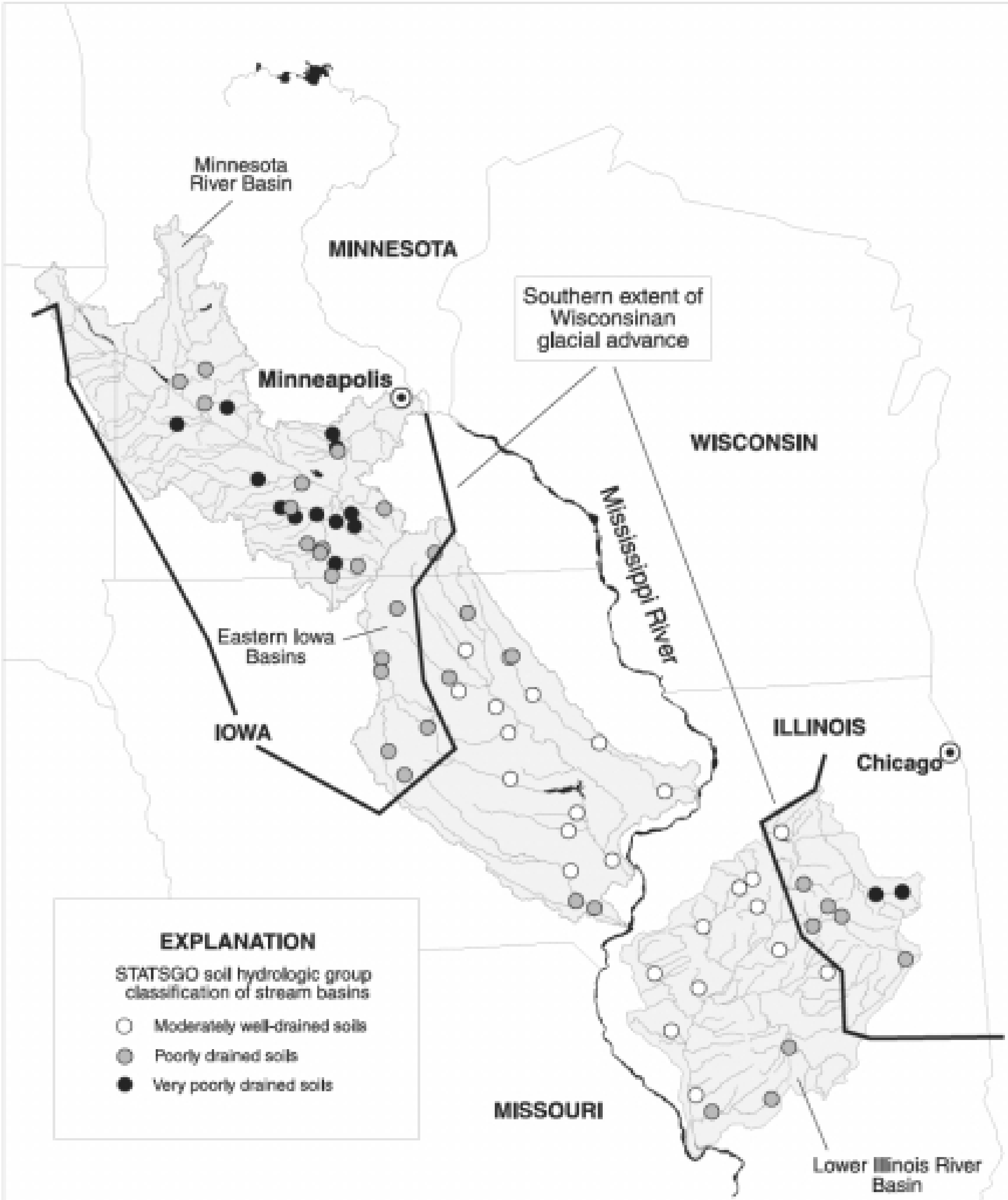


Figure A-11. Classification of Midwestern streams and rivers relative to basin soil-drainage characteristics and relation with southern extent of Wisconsin glacial advance.

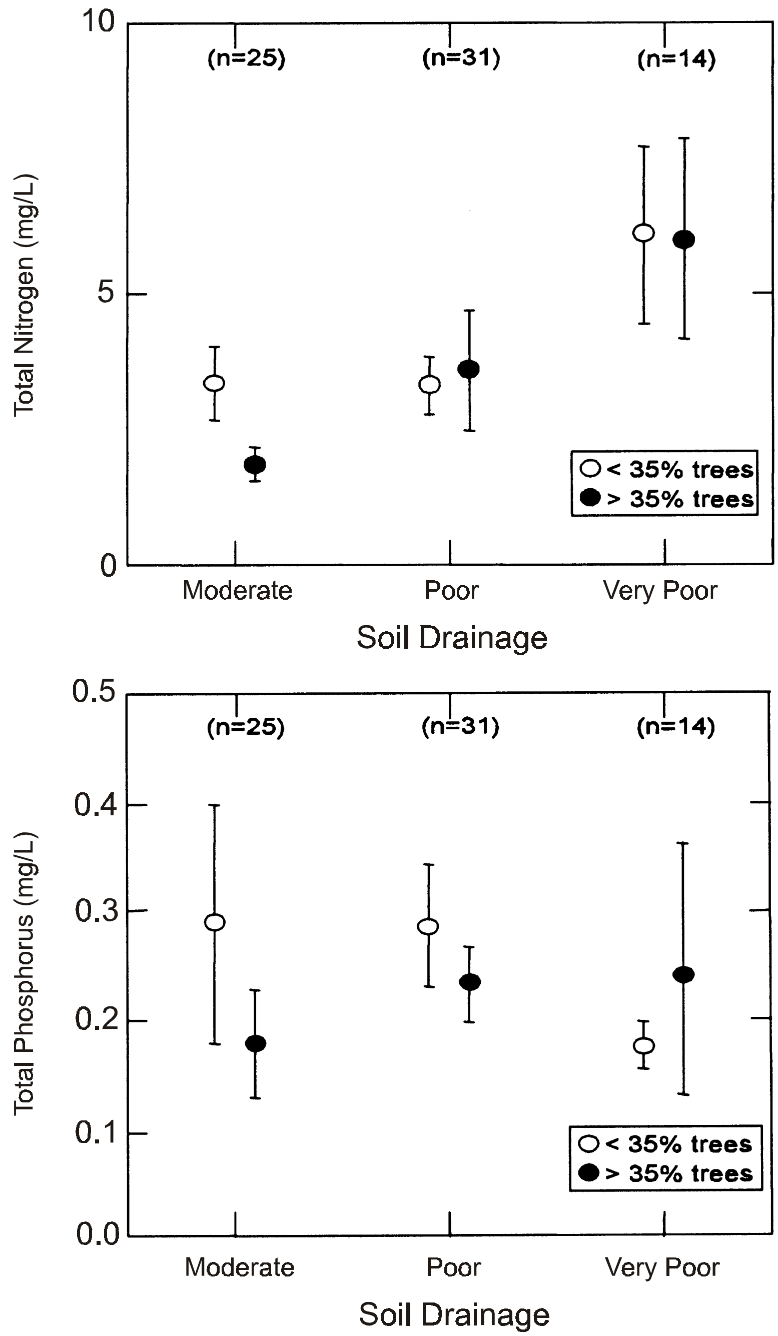


Figure A-12. Total nitrogen and phosphorus concentrations relative to soil drainage and riparian conditions in Midwestern streams and rivers.

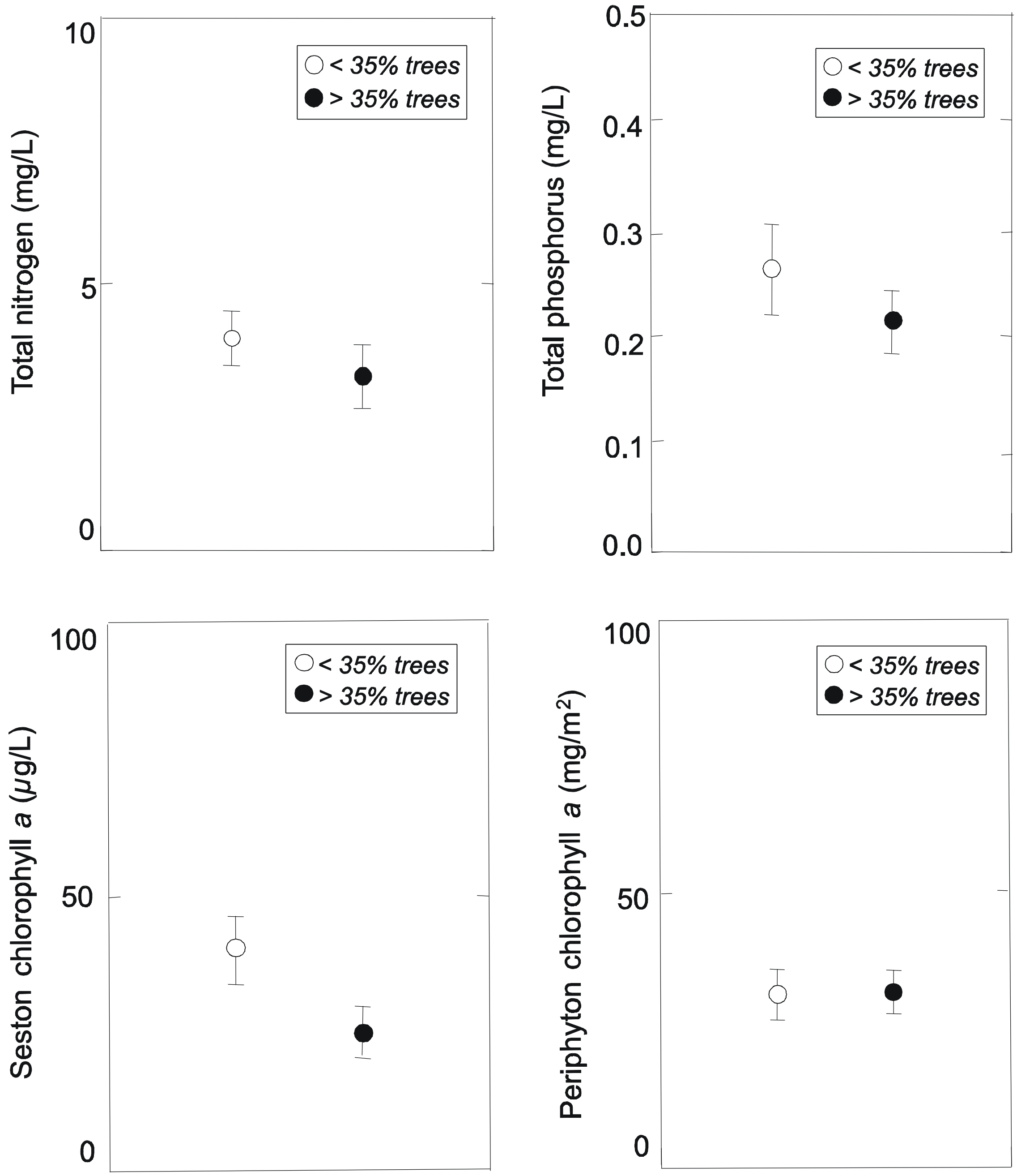
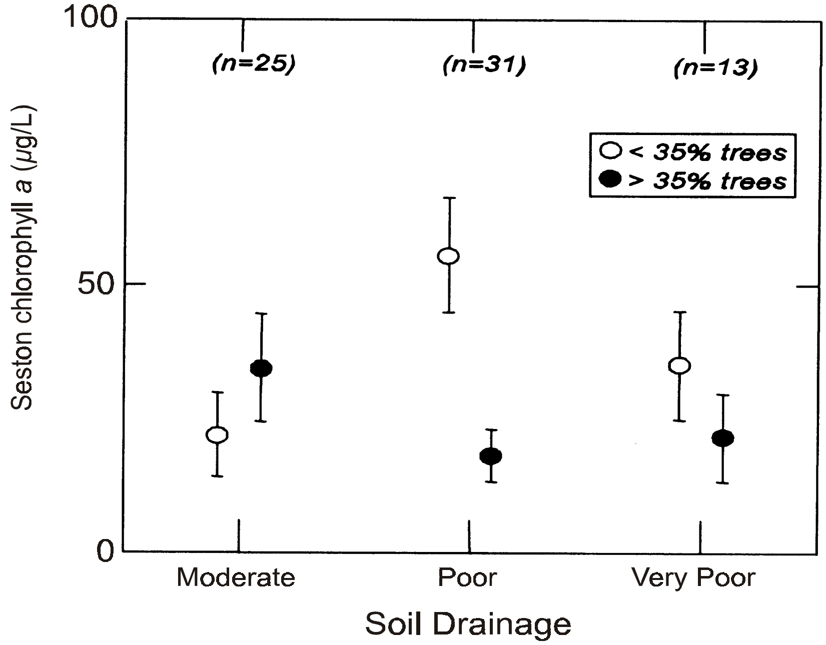


Figure A-13. Average concentrations of total nitrogen, total phosphorus, seston chlorophyll *a*, and periphyton chlorophyll *a* in relation to riparian-zone conditions.

Table A-2. Distribution of algal seston, periphyton, ash-free dry mass, stream productivity and respiration, suspended and dissolved carbon, total suspended solids, and water clarity (euphotic zone depth) in Midwestern agricultural streams and rivers.

Water quality constituent	10th percentile	25th percentile	50th percentile (median)	75th percentile	90th percentile	Maximum value
Seston chlorophyll *a* (mg/L)	6.40	11.0	18.4	38.7	71.7	175
Periphyton chlorophyll *a* ($\mu g/m^2$)	3.67	13.1	25.1	42.2	72.6	102
Periphyton ash-free dry mass (g/m^2)	15.7	19.3	25.4	31.5	39.5	57.8
Stream productivity ($g\ O_2/m^3/hr$)	0.113	0.242	0.398	0.697	0.998	1.46
Stream respiration ($g\ O_2/m^3/hr$)	0	0	-0.044	-0.159	-0.226	-0.804
Suspended organic carbon (mg/L)	0.5	0.7	1.3	2.5	3.6	5.0
Dissolved organic carbon (mg/L)	2.4	3.6	4.3	5.8	7.2	11
Total Suspended Solids (mg/L)	19	41	72	128	158	330
Estimated euphotic zone depth (m)	0.32	0.42	0.56	0.68	0.84	1.4



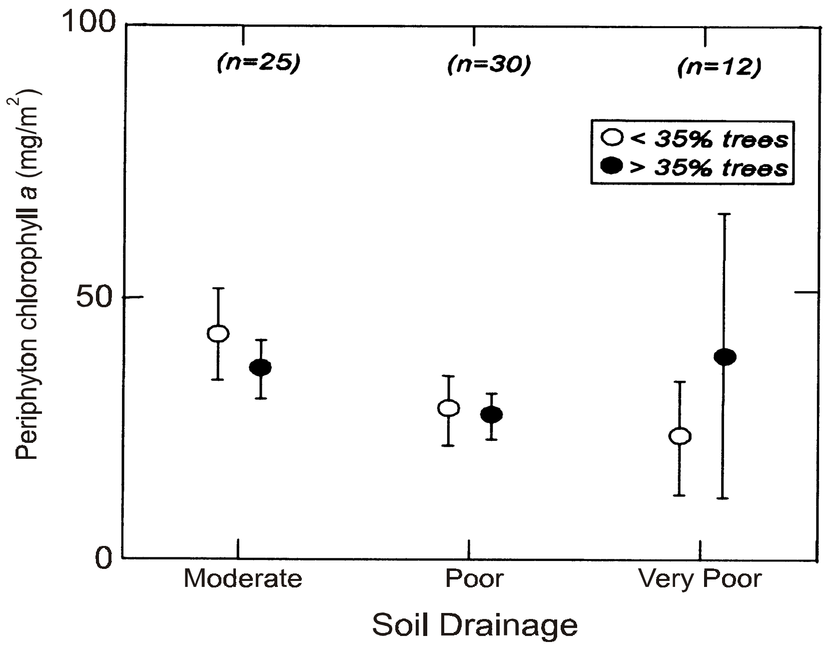


Figure A-14. Seston and periphyton chlorophyll a values relative to soil drainage and riparian conditions in Midwestern streams and rivers.

and relatively large populations of hogs and other livestock. Stream productivity (P_{max}) and respiration (R_{max}) values increased significantly with seston chl *a* concentrations. Concentrations of NO_2+NO_3-N decreased significantly with increases in stream productivity, which is probably correlated with algal uptake of dissolved nutrients. Seston chl *a* concentrations were positively correlated with concentrations of suspended organic carbon (SOC), TON, particulate phosphorus, and total suspended sediment (TSS), which suggests that total nutrient and organic enrichment in Midwestern streams is reflected by large populations of algal seston. Seston chl *a* concentrations were negatively correlated with euphotic zone depth, indicating that water clarity decreases with increases in the abundance of suspended algae (phytoplankton).

Periphyton chl *a* values were significantly larger in streams with high water clarity and riparian shading, and above-average stream velocity. Concentrations of total and dissolved nutrients and seston chl *a* in periphyton-dominated streams were generally moderate to low; however, productivity (P_{max}) was about average for Midwestern streams, suggesting that periphyton (rather than seston) influences the productivity of streams with high riparian shading and appreciable ground-water discharge. Large populations of diatoms and blue-green algae were observed growing on sand (near the hyporheic zone) in these streams. Although concentrations of NH_4-N and DoP were larger in streams that drain basins with moderately-well drained soils, regionally, periphyton uptake of dissolved nutrients from ground-water discharges might account for the lower-than-expected concentrations of these constituents in the Wapsipinicon and Cedar River basins of eastern Iowa. While P_{max} rates in periphyton-dominated streams were near average regionally, rates of stream respiration (R_{max}) were generally low, and early-morning concentrations of DO appeared to be favorable for aquatic life. In contrast, rates of R_{max} were relatively high in seston-dominated streams; DO concentrations during early-morning hours were low and benthic macroinvertebrate community structure was poor (Harris and Porter in review).

Periphyton chl *a* and ash-free dry mass (AFDM) values were positively correlated; however, chl *a* and AFDM relations (refer to Table A-2) differed with respect to precedent stream-flow conditions, water clarity, and non-algal sources of carbon. Ratios of chl *a* to AFDM were relatively low (less than one) in over half the streams in the Minnesota River basin, where the organic content of soils is relatively high and soil drainage is very poor. In addition, above-average stream flow and water turbidity, as well as a higher frequency of hydrologic disturbances associated with summer storms during the months prior to the study (Figure A-15) probably limited the growth of algal periphyton in the Minnesota River basin. In contrast, chl *a*/AFDM ratios were larger (greater than one) in streams with relatively stable stream flow and good water clarity.

Periphyton samples were analyzed for species composition and abundance (cells/cm^2), and the biovolume of each algal taxon was determined by measuring cell dimensions and calculating the average volume of the cell (μm^3) in relation to the nearest geometric shape (e.g., sphere, cylinder, etc.). Biovolume ($\mu m^3/cm^2$) for each species was calculated by multiplying the volume of one cell by the abundance of the species in the sampling reach. Total algal biovolume (cm^3/m^2) was estimated by summing biovolumes for all species present in the sample. Total algal biovolume (TAB) is positively correlated with periphyton chl *a* and AFDM, and periphyton chl *a* can be estimated from TAB using the following regression relation:

$$\text{chl } a = (4.229 + 2.733 * \log_{10}(\text{TAB}))^2 \qquad \text{adjusted } R^2=0.570;\ p<0.001;\ n=67$$

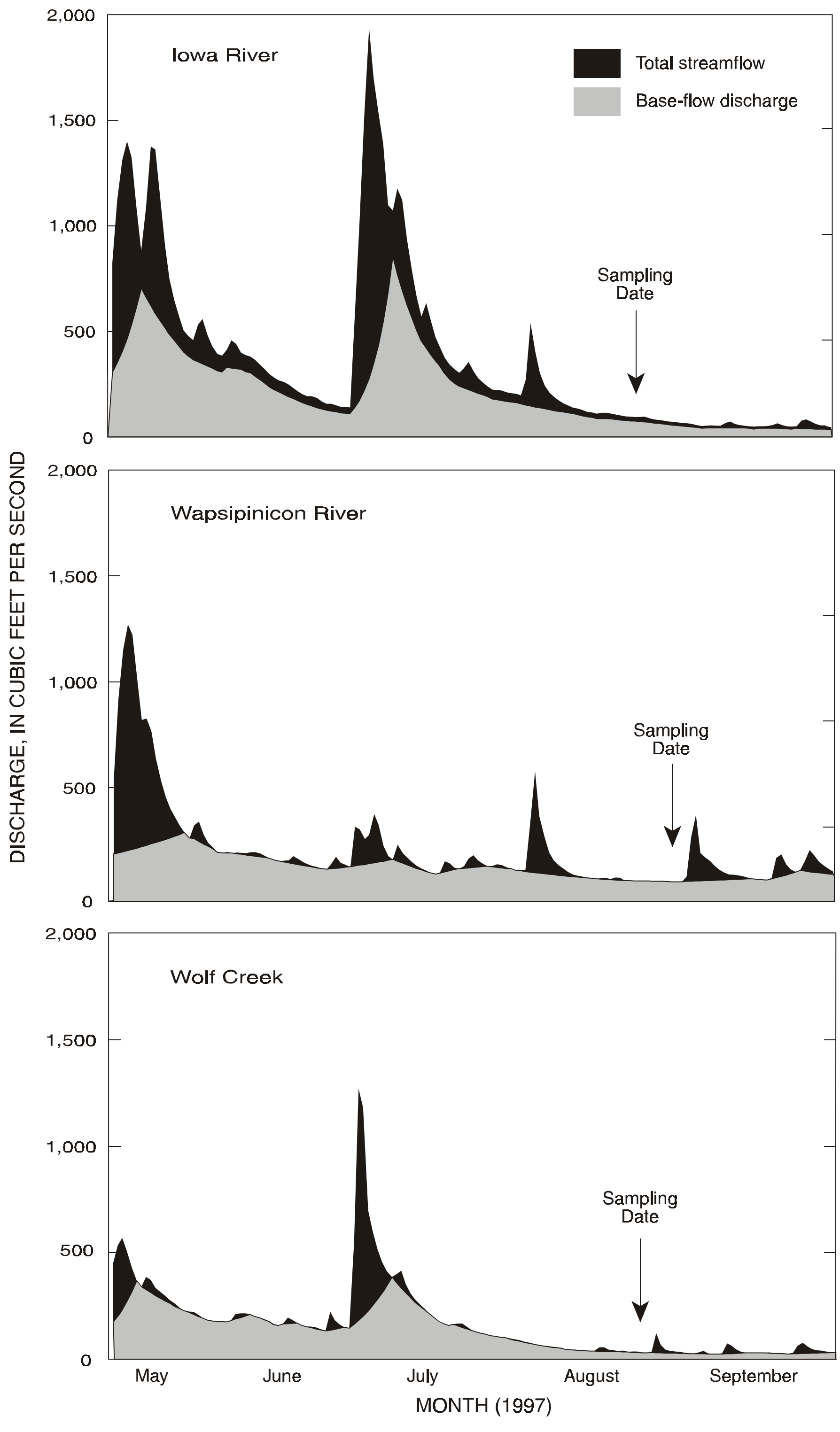


Figure A-15. Total and base flow discharge for selected Midwestern streams and rivers in relation to collection date of water quality samples.