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SUGGESTED CLASSIFICATION OF STREAM TROPHIC STATE: DISTRIBUTIONS OF TEMPERATE STREAM TYPES BY CHLOROPHYLL, TOTAL NITROGEN, AND PHOSPHORUS

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Abstract—Aquatic scientists and managers have no conventional mechanism with which to characterize and compare nutrients and algal biomass in streams within a broader context analogous to trophic state categorization in lakes by chlorophyll (chl) and nutrients. We analyzed published data for a large number of distinct, temperate, stream sites for mean benthic chl ($n = 286$), maximum benthic chl ($n = 176$), sestonic chl ($n = 292$), total nitrogen ($n = 1070$), and total phosphorus ($n = 1366$) as a first effort to establish criteria for trophic boundaries. Two classification systems are proposed. In the first system, the boundary between oligotrophic and mesotrophic categories is defined by the lower third of the cumulative distribution of the values. The mesotrophic–eutrophic boundary is defined by the upper third of the distribution. In the second system, individual streams are placed more precisely in a broad geographic context by assessing the proportion of streams that have greater or lesser nutrient and chl values. The proposed relationships for streams were compared to trophic criteria published for lakes. The proposed trophic boundaries for streams generally include a broader range of values in the mesotrophic range than conventional criteria for lakes. The ratio of maximum to mean benthic chl for streams was significantly higher than that found for planktonic chl in lakes, reflecting the greater variance in streams. This high variance in streams suggests that the proposed stream trophic criteria should be viewed only as a general first approach to categorizing stream ecosystems. © 1998 Elsevier Science Ltd. All rights reserved

Key words—chlorophyll, eutrophic, mesotrophic, nitrogen, nutrients, oligotrophic, periphyton, phosphorus, rivers, streams

INTRODUCTION

Classification of ecosystems by an index of trophic state is common in the aquatic sciences. Streams occasionally are classified as eutrophic or oligotrophic (e.g. Hornberger *et al.*, 1977; Kelly and Whitton, 1995), but no conventional criteria exist for these terms when applied to lotic systems. Stream enrichment often leads to increases in algal biomass (e.g. Dodds *et al.*, 1997; Lohman *et al.*, 1992, Van Niewenhuyse and Jones, 1996; Welch *et al.*, 1992), and thus, a trophic classification using both nutrients and algal biomass seems useful as it has been for lakes. Autotrophic biomass is important in many streams as a food source for organisms (Lamberti, 1996). Being able to place a stream in a continuum of nutrient concentrations and producer biomass from a variety of temperate streams should aid stream researchers and managers in characterizing ecosystems and facilitate comparative research and management.

Conventional systems exist for classifying lakes into trophic categories using nutrients and algal biomass (e.g., OECD, 1982; Porcella *et al.*, 1980; Ryding and Rast, 1989). Trophic classifications for lakes have a rich history and stem from differences in lake ecosystem function and phytoplankton communities over the range of lake types (Hutchinson, 1967). General functional characteristics exist among lakes within each of the major trophic state categories. Simply put, oligotrophic lakes have low nutrients, low algal biomass, high clarity, and deep photic zones, and may support a cold-water fishery. Eutrophic lakes can have frequent cyanobacterial blooms, high total nutrients, and wide swings in dissolved oxygen (DO) concentrations (potential anoxia) and pH. Mesotrophic lakes have intermediate characteristics. The boundaries placed between these categories by aquatic scientists are similar but not universal (e.g., Forsberg and Ryding, 1980; OECD, 1982; Porcella *et al.*, 1980), in part because

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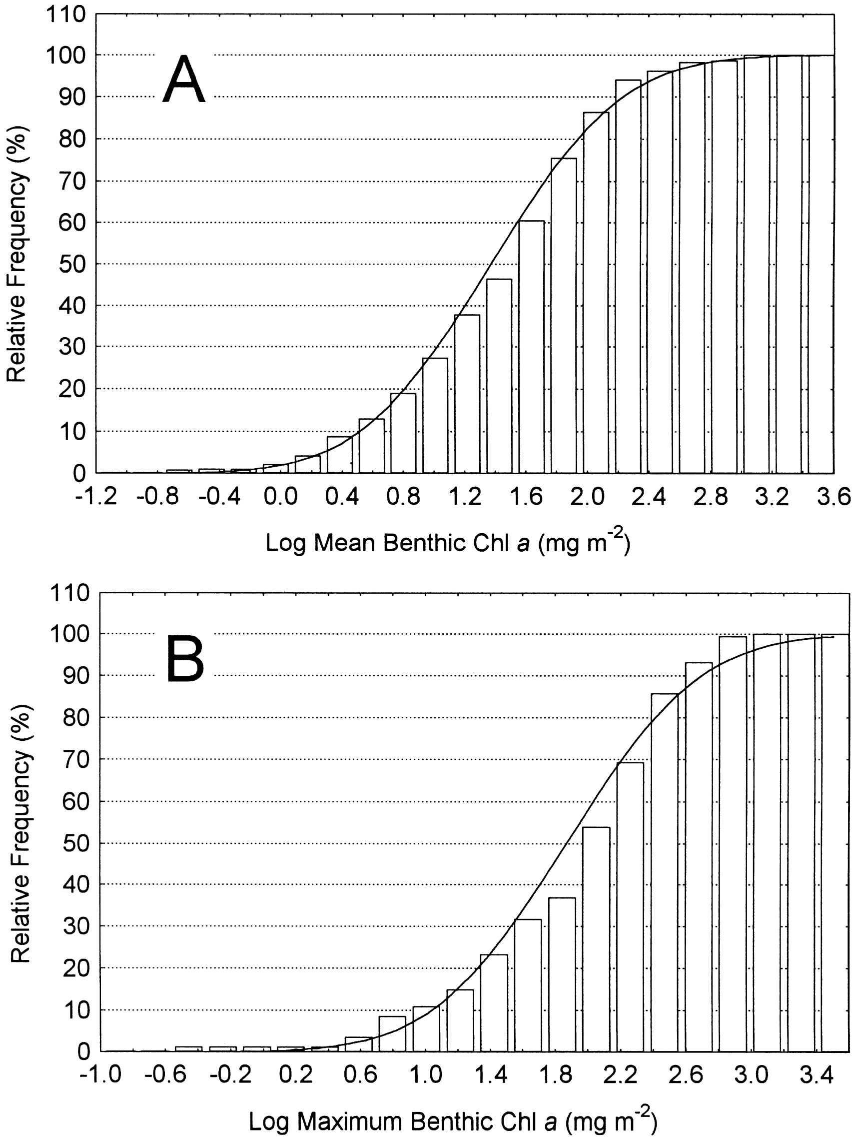


Fig. 1. Cumulative frequency diagram of seasonal mean (A, $n = 286$) and maximum (B, $n = 176$) benthic chl *a*. The line indicates the log–normal distribution. The distribution of mean benthic chl was not significantly different from the log–normal distribution ($p < 0.15$), but that of maximum chl was ($p < 0.005$, Kolmogorov–Smirnov).

the perceptions of researchers have provided the basis for most schemes and true geographic differences exist among lakes that justify modifying criteria for specific regions (Jones and Knowlton, 1993). Alternatively, Carlson (1977) constructed a Trophic State Index (TSI) on a scale of 0 to 100 based on interrelations among chlorophyll (chl), total phosphorus (TP), and Secchi depth. Each 10 units within this system represent a doubling of TP, a one-third increase in chl, and a half decrease in Sechhi depth, thus providing a basis for the scale and a means to identify nutrient-limited conditions (Carlson, 1991).

Stream ecosystems have been described on the basis of carbon sources (Dodds, 1997) and position in the watershed (Vannote *et al.*, 1980), but boundaries separating stream types based on producer biomass and nutrients across watersheds are lacking. Stream nutrients usually have been observed to increase as a function of intensity of land use within the basin (Omernik, 1977; Smart *et al.*, 1985) and with human population density in the watershed (Peierls *et al.*, 1991). Historically, specific zones within streams have been identified in relation to point source inputs of organic pollution and its impact on dissolved O_2, nutrient content and stream

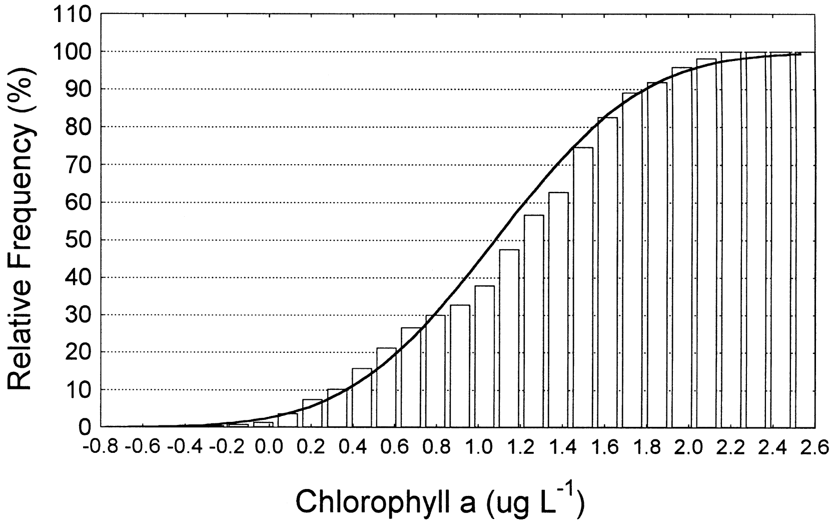


Fig. 2. Cumulative frequency diagram of sestonic chl for temperate streams (n = 292). The line indicates the log–normal distribution, which was not significantly different from this distribution ($p < 0.07$, Kolmogorov–Smirnov).

biota (Bartsch and Ingram, 1959). These identifications dealt primarily with longitudinal zones of degradation and recovery but did not allow characterization of the fertility and productivity of individual streams relative to others. A trophic index based on diatoms was proposed for use in the United Kingdom (Kelly and Whitton, 1995), but this index is specific to a limited region, requires sophisticated taxonomic skills that are not generally available, and excludes filamentous green algae which are most commonly associated with nuisance conditions. Photosynthesis/respiration ratios also have been suggested as a method to characterize trophic state in streams (Hornberger *et al.*, 1977), but this characterization requires intensive monitoring of diel variations in dissolved oxygen concentrations and has received little use.

We propose a simple approach for initially characterizing trophic state of streams using the frequency distributions of nutrients and chl to define the three trophic categories. This approach is appropriate given the absence of natural trophic boundaries based on stream ecosystem characteristics. Using the distribution of values across a large number of temperate streams, the lowest third represents the oligotrophic category, the middle third the mesotrophic category, and the top third is proposed to constitute the eutrophic category. These frequency diagrams also allow individual streams or streams within a specific geographic area to be placed in a broader context of stream types (Omernik, 1977). For example, it may be more persuasive to argue that a specific stream is eutrophic if 70% of the streams in this data set have less chl *a*. We used previously published data for our analyses.

SOURCES OF DATA

Data on mean and maximum benthic stream chl, and some of the mean water-column total nitrogen (TN), and mean TP were taken from a previously published data set for temperate streams (Dodds *et al.*, 1997). These data were collected for more than 200 streams or sites in North America and New Zealand. The majority of the systems were from temperate habitats. Seasonal means from a single year (for 2 to 3-month periods) generally were used for TN, TP and mean benthic chl. These were not always restricted to summer, because some streams (e.g., those with deciduous tree cover) may have more biomass or production at other times of the year. Seasonal maxima also were taken from this data set. The data set included sites from low order streams up to large rivers, and from nutrient enriched to those with pristine vegetative cover.

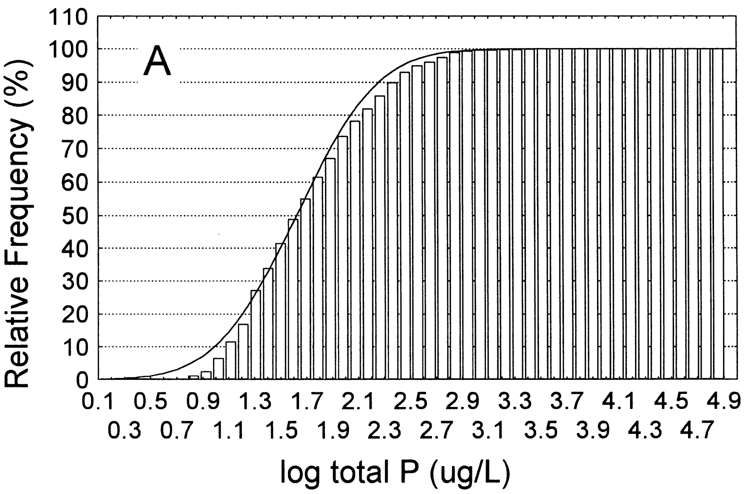
Data on planktonic (sestonic) chl and some of the water column TP data were taken from a different data set (Van Niewenhuyse and Jones, 1996). These data came from 115 streams for multiple sites and years (almost 300 separate data points) from a variety of watershed types and areas in the temperate zone (primarily North America, with some European streams represented). All TP and chl in this data set were calculated as growing season means.

Additional data on water column TN and TP were taken from a compilation of stream data from the United States Environmental Protection Agency National Eutrophication Survey (Omernik, 1977). These values are represented by means from approximately monthly sampling of 928 streams over a period of a year. The streams sampled in this study were generally small, with watershed use distributed from pristine forests to fully agricultural.

RESULTS AND DISCUSSION

Wide distributions of mean and maximum benthic chl, and water column chl, TN, and TP were observed within the data sets (Figs 1–3). Some of the distributions were not significantly different from a log–normal distribution, but those for maximum chl and TN were. For this reason, the actual data distributions were used to set trophic classification boundaries. The approximate values marking the divisions between the lower and middle thirds, and between the middle and upper thirds of each distribution were used as boundaries between oligotrophic and mesotrophic and between mesotrophic and eutrophic, respectively (Table 1). Sharp, natural boundaries in trophic state and functional relations among the variables have yet to be identified for streams, so these boundaries should be viewed as provisional. The boundaries will likely change somewhat as the database expands, sites from tropical and polar regions are added, macrophytes are considered, and functional relationships among nutrients and algal biomass are developed further in lotic systems. Nevertheless, the suggested boundaries provide general guides to divide the trophic continuum.

Our trophic categories match another trophic characterization proposed on the basis of watershed characteristics for 16 New Zealand streams (Biggs, 1996). The 16 New Zealand streams were divided into unenriched, moderately enriched, and enriched categories based upon the amount of agriculture and geology in each individual watershed. Then the cumulative frequency distributions were plotted for benthic chl. About 90% of the values in the unen-



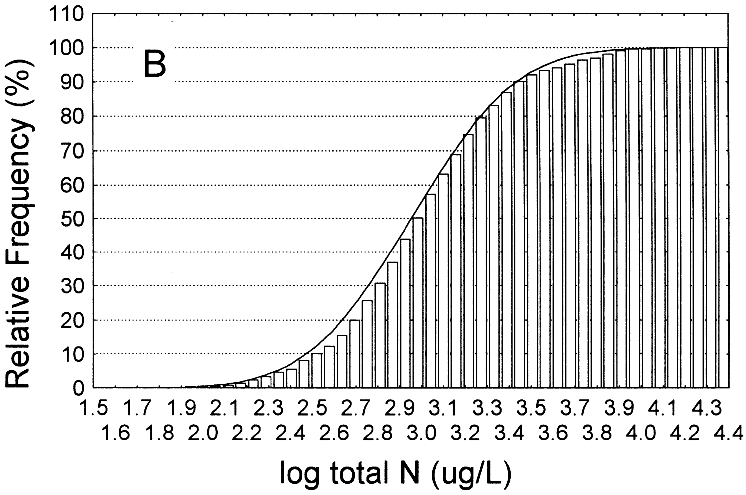


Fig. 3. Cumulative frequency diagram of TP (A, $n = 1366$) and TN (B, $n = 1070$) for temperate streams. The line indicates the log–normal distribution. The TN distribution was significantly different than the log–normal distribution ($p < 0.02$) but the TP distribution was not ($p < 0.07$, Kolmogorov–Smirnov).

Table 1. Suggested boundaries for trophic classification of streams from cumulative frequency distributions in Figs 1–3. The boundary between oligotrophic and mesotrophic systems represents the lowest third of the distribution, and the boundary between mesotrophic and eutrophic marks the top third of the distribution

Variable (units)	Oligotrophic–mesotrophic boundary	Mesotrophic–eutrophic boundary	N
Mean benthic chlorophyll (mg m^{-2})[a]	20	70	286
Maximum benthic chlorophyll (mg m^{-2})[a]	60	200	176
Sestonic chlorophyll (μg l^{-1})[b]	10	30	292
TN (μg l^{-1})[a,c]	700	1500	1070
TP (μg l^{-1})[a,b,c]	25	75	1366

[a]Data from Dodds *et al.* (1997).
[b]Data from Van Niewenhuyse and Jones (1996).
[c]Data from Omernik (1977).

riched and moderately enriched watersheds fell below 20 and 100 mg m^{-2} chl respectively. These categories compare favorably to our proposed upper boundaries of 20 and 70 mg m^{-2} chl for oligotrophic and mesotrophic systems respectively.

The cumulative frequency diagrams (Figs 1–3) depict the broad variation inherent in stream chl and nutrient chemistry when many streams are considered. The diagrams also provide a relative scale to locate individual streams of interest along a larger continuum of nutrients and chl. For example, a stream may be considered to be moderately enriched if TN is 1000 μg/l because about 50% of the streams in our data set have less N (Fig. 3B). Comparisons of this type may also help identify functional processes in streams. If a stream has TP levels in the top 10% of our distribution and either benthic or sestonic chl in the bottom 10%, some factor other than nutrients likely is controlling accrual of biomass. Specific functions to determine the expected relationships between TN:TP and benthic chl (Dodds *et al.*, 1997) and TP and sestonic chl (Van Niewenhuyse and Jones, 1996) are available, if more detailed analysis is required.

Previous studies have suggested that benthic chl above 50–200 mg m^{-2} may represent a cut point for nuisance conditions (Table 2). These values of chl have been determined subjectively and there may be a regional basis for the four-fold range. However, most of these objectionable levels fall above the proposed lower boundary for eutrophic streams (Table 1). About 85% of the streams analyzed in our database had mean benthic chl below 100 mg m^{-2}, and 50% had maximum values below this level. Therefore, a general suggestion that a mean of 150 mg m^{-2} represents nuisance levels agrees with values suggested by other authors (Table 2).

A positive relationship occurred between seasonal mean and maximum stream benthic chl (Fig. 4). The ratio of maximum to mean benthic chl for our data set was 4.52 (n = 178, std. dev. = 7.61, lower 95% confidence level 3.39). The ratio of maximum to mean chl in lakes has been reported to be 1.7–1.8 by Jones *et al.* (1979), 2.5 by Chapra and Tarapchak (1976), and 2.6 by OECD (1982). This significantly higher ratio for streams and rivers than for lakes indicates the higher potential variability in chlorophyll in streams. Probably this higher ratio for streams can be explained by the influence of scouring floods (Allan, 1995; Peterson, 1996). Such hydrologic fluctuations between flood and base flow have been demonstrated to greatly influence stream chemical constituents and autotrophic biomass (Lohman *et al.*, 1992; Perkins and Jones, 1994), and these temporal changes complicate stream characterization.

The papers that analyze nutrient chlorophyll relationships in streams more thoroughly (Dodds *et al.*, 1997; Van Niewenhuyse and Jones, 1996) have demonstrated relationships between TN or TP and chl for streams that are weaker than they are in lakes. This is probably because high turbidity (non-algal TN and TP) may be more common in streams than in lakes. Also, our cumulative frequency distributions for TN and TP contained a large number of points for which no chl data were available. Therefore, it may not be advisable to attempt to tightly link distributions of TN or TP concentrations to the benthic chl distributions presented here.

We evaluated our trophic criteria for streams against those published for lakes because trophic state characterization for lakes is more established through actual use. We compared the areal phytoplankton chl content in lakes to benthic chl in

Table 2. Suggested criteria from various studies for maximum benthic biomass (as chl) levels to avoid problems for recreational and aesthetic use in streams

Suggested value or range (mg chl m^{-2})	Comment	Reference
150–200	based on perceived impairment	Welch *et al.*, 1989
100–150	based on 19 enrichment cases and surveys	Welch *et al.*, 1988, Horner *et al.*, 1983
150	guidelines for Clark Fork River Montana, U.S.A.	Tristate Implementation Council, 1996
50–100	British Columbia Environment guideline	Nordin, 1985

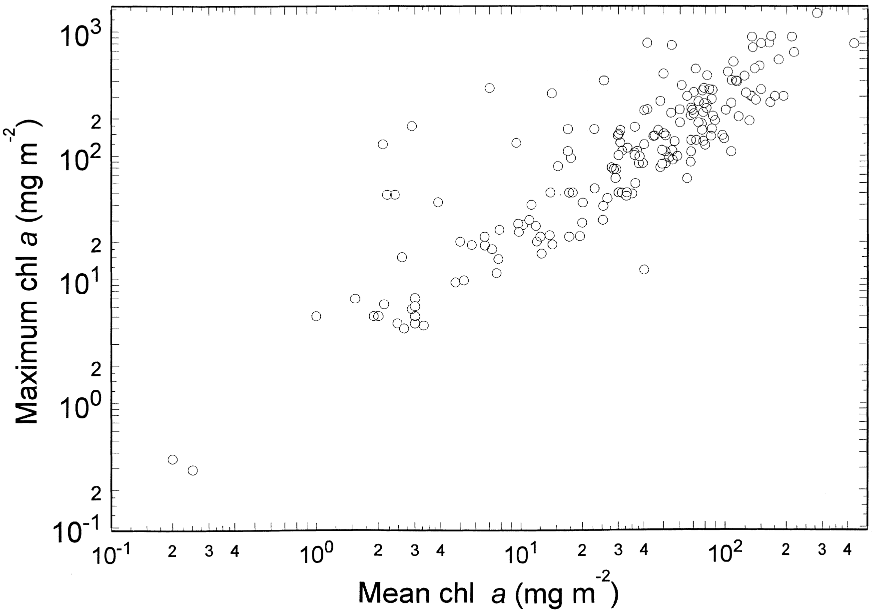


Fig. 4. Relationship between seasonal mean and maximum benthic chl for 176 temperate streams.

streams and volumetric planktonic chl concentrations in lakes and streams. A popular fixed boundary system for trophic classification (OECD, 1982), using chl, TN, TP, and Secchi depth, was employed for this comparison (Table 3). Assuming that chl is distributed evenly down to two times the Secchi depth (roughly the compensation point for photosynthesis), we also calculated areal chlorophyll values for lakes. These data suggest that the OECD (1982) mesotrophic range for areal chl in lakes is slightly narrower than the range for streams. This could be because chl (on an areal basis) is distributed differently in lakes than in streams or the methods used to define trophic state in lakes led to drawing boundaries at different levels. The reader should keep in mind how the OECD (1982) system was constructed. Data were provided for a large number of lakes by a number of investigators. Each investigator signified if their lakes were oligotrophic, mesotrophic or eutrophic. The boundaries for each trophic classification were then derived for all lakes proposed for each of the three categories.

We used our cumulative frequency method to define boundaries for lakes in a similar fashion as that used for streams. When Smith (1982) data for approximately 309 lakes and Jones and Knowlton (1993) data for 94 reservoirs were used, the trophic boundaries for chl *a*, TN, and TP of lakes were similar to those proposed for streams in this paper. In fact, TP boundaries for lakes and streams from cumulative frequency distributions were virtually identical. Thus, our trophic classifications for streams may vary from the OECD values for lakes largely because of methodology. That is, a statistical approach to classification of lake trophic state

Table 3. Trophic boundaries for lakes from OECD (1982) and lake data reanalyzed using methods in this paper

Variable	Oligotrophic–mesotrophic boundary	Mesotrophic–eutrophic boundary
OECD-based values		
Volumetric mean planktonic chl (μg l^{-1})[a]	2.5	8
Volumetric maximum chl (μg l^{-1})[a]	8	25
TP (μg l^{-1})[a]	10	35
Mean Secchi (m)[a]	6	3
A real mean planktonic chl (mg m^{-2})[b]	30	48
Based on cumulative frequency distributions from lakes		
Planktonic mean chl (μg l^{-1})[c]	8	25
TP (μg l^{-1})[c]	25	71
TN (μg l^{-1})[c]	500	1260

[a]OECD, 1982 values.
[b]Calculated from OECD (1982) assuming chlorophyll is distributed evenly to 2 times the Secchi depth.
[c]Smith (1982) data, $n = 309$, and Jones and Knowlton (1993) data, $n = 94$ for Missouri Reservoirs, with the cumulative frequency method proposed here applied to determine trophic state.

yielded categories for lakes more similar to those proposed here for streams, whereas the more subjective methods used by others for lakes yielded trophic classifications less similar to ours.

The distributions presented here can be refined as more data become available, particularly for benthic and suspended chl. Tropical streams and rivers may vary from their temperate counterparts analyzed here. Eutrophic streams may be more abundant in particular geographic regions. For example, areas with considerable agricultural activity typically have streams with high nutrient content (Omernik, 1977). Detailed analysis in specific regions may lead to categorization of streams that has more geographic relevance (e.g. Biggs, 1995; Biggs, 1996). It is also certain that the distributions we report are influenced by anthropogenic nutrient sources and do not represent pristine, background conditions. The past can not be re-visited and there are virtually no large, completely pristine temperate rivers left to construct a data base from, so the next best approach is to provide a baseline using data collected over the past few decades. We suggest that frequency distributions can be used to assist stream scientists and managers in determining the trophic states of their individual streams relative to others.

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REFERENCES

Allan J. D. (1995) *Stream Ecology*. Chapman and Hall, London.

Bartsch A. F. and Ingram W. M. (1959) Streamlife and the pollution environment. *Publ. Works* **90,** 104–110.

Biggs B. J. F. (1995) The contribution of flood disturbance, catchment geology and land use to the habitat template of periphyton in stream ecosystems. *Freshwater Biol.* **33,** 419–438.

Biggs B. J. F. (1996) Patterns in benthic algae in streams, In *Algal Ecology* (Edited by Stevenson R. J., Bothwell M. L., Lowe R. L.), pp. 31–56. Academic Press. San Diego.

Carlson R. E. (1977) A trophic state index for lakes. *Limnol. Oceanogr.* **22,** 361–369.

Carlson R. E. (1991) Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs, *Enhancing the States' Lake Management Programs*, pp. 59–71. North American Lake Management Society.

Chapra S. C. and Tarapchak S. J. (1976) A chlorophyll *a* model and its relationship to phosphorus loading plots for lakes. *Wat. Resour. Res.* **12,** 1260–1264.

Dodds W. K. (1997) Distribution of runoff and rivers related to vegetative characteristics, latitude, and slope: a global perspective. *J. N. Am. Benthol. Soc.* **16,** 162–168.

Dodds W. K., Smith V. H., Zander B. (1997) Developing nutrient targets to control benthic chlorophyll levels in streams: a case study of the Clark Fork River. *Wat. Res.* **31,** 1738–1750.

Forsberg C. and Ryding S.-O. (1980) Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. *Arch. Hydrobiol.* **89,** 189–207.

Hornberger G. M., Kelly M. B. and Cosby B. J. (1977) Evaluating eutrophication potential from river community productivity. *Wat. Res.* **11,** 65–69.

Horner R. R., Welch E. B. and Venestra R. B. (1983) Development of nuisance periphytic algae in laboratory streams in relation to enrichment and velocity. In *Periphyton of Freshwater Ecosystems* (Edited by Wetzel R. G.). pp. 121–134. Junk, The Hauge.

Hutchinson G. E. (1967) *A Treatise on Limnology*, Vol 2. Wiley, New York.

Jones R. A., Rast W. and Lee G. F. (1979) Relationships between summer mean and maximum chlorophyll *a* concentrations in lakes. *Environ. Sci. Technol.* **13,** 869–870.

Jones J. R. and Knowlton M. K. (1993) Limnology of Missouri reservoirs: An analysis of regional patterns. *Lake Reserv. Manage.* **8,** 17–30.

Kelly M. G. and Whitton B. A. (1995) The trophic diatom index: a new index for monitoring eutrophication in rivers. *J. Appl. Phycol.* **7,** 4232–4244.

Lamberti G. A. (1996) The niche of benthic food webs in freshwater ecosystems, In *Algal Ecology*, *Freshwater Benthic Ecosystems* (Edited by Stevenson R. J., Bothwell M. L., Lowe R. L.), pp. 553–564. Academic Press, San Diego.

Lohman K., Jones J. R. and Perkins B. D. (1992) Effects of nutrient enrichment and flood frequency on periphyton biomass in northern Ozark streams. *Can. J. Fish. Aquat. Sci.* **49,** 1198–1205.

Nordin R. N. (1985) Water quality criteria for nutrients and algae (technical appendix). Water Quality Unit, Resource Quality Section, Water Management Branch, B. C. Ministry of Environment, Victoria.

OECD (Organization for Economic Cooperation and Development) (1982) Eutrophication of Waters. Monitoring assessment and control. Final Report. OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Environment Directorate, OECD, Paris, 154 p.

Omernik J. M. (1977) Nonpoint source-stream nutrient level relationships: a nationwide study. Special Studies Branch Corvallis Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. EPA-600/3-77-105.

Peierls B. L., Caraco N. F., Pace M. L. and Cole J. J. (1991) Human influence on river nitrogen. *Nature* **350,** 386–387.

Perkins B. D. and Jones J. R. (1994) Temporal variability in a Midwestern stream during spring. *Verh. Int. Verein. Limnol.* **25,** 1471–1476.

Peterson C. G. (1996) Response of benthic algal communities to natural physical disturbance. In *Algal Ecology*, *Freshwater Benthic Ecosystems* (Edited by Stevenson R. J., Bothwell M. L., Lowe R. L.), pp. 375–402. Academic Press, San Diego.

Porcella D. B., Peterson S. A. and Larsen D. P. (1980) Index to evaluate lake restoration. *J. Environ. Eng.* **106,** 1151–1169.

Ryding S.-O. and Rast W. (1989) *The Control of Eutrophication of Lakes and Reservoirs*. Vol. I. UNESCO, Paris and Parthenon, United Kingdom. 314 pp.

Smart M. M., Jones J. R. and Sebaugh J. S. (1985) Stream-watershed relations in the Missouri Ozark plateau province. *J. Environ. Qual.* **14,** 77–82.

Smith V. H. (1982) The nitrogen and phosphorus dependence of algal biomass in lakes: an empirical and theoretical analysis. *Limnol. Oceanogr.* **27,** 1101–1112.

Tristate Implementation Council (1996) Clark Fork River voluntary nutrient reduction program. Nutrient Target

DWR-758

Subcommittee draft report. Montana Department of Environmental Quality, Helena, MT.

Van Niewenhuyse E. E. and Jones J. R. (1996) Phosphorus-chlorophyll relationships in temperate streams and its variation with stream catchement area. *Can. J. Fish. Aquat. Sci.* **53,** 99–105.

Vannote R. L., Minshall L. W., Cummins K. W., Sedell J. R. and Cushing C. E. (1980) The river continuum concept. *Can. J. Fish. Aquat. Sci.* **37,** 130–137.

Welch E. B., Jacoby J. M., Horner R. R. and Seeley M. R. (1988) Nuisance biomass levels of periphytic algae in streams. *Hydrobiologia* **157,** 161–168.

Welch E. B., Horner R. R. and Patmont C. R. (1989) Prediction of nuisance periphytic biomass: a management approach. *Wat. Res.* **23,** 401–405.

Welch E. B., Quinn J. M. and Hickey C. W. (1992) Periphyton biomass related to point-source nutrient enrichment in seven New Zealand streams. *Wat. Res.* **26,** 669–675.