New England Interstate Water Pollution Control Commission

The Relationship Between Nutrient Concentrations and Periphyton Levels in Rivers and Streams - A Review of the Scientific Literature

FINAL

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

Acronyms

AFDM	Ash free dry mass
Ca	Calcium
CSA	Cambridge Scientific Abstracts
Chl a	Chlorophyll a biomass (mg/m^2)
Cond	Conductivity
d_a	Mean days of accrual
DO	Dissolved oxygen
DIN	Dissolved Inorganic Nitrogen
FTU	Formazine Turbidity Unit
JCU	Jackson Candle Unit
n	Number of data points in sample set
N	Nitrogen
na	Data not available
NEIWPCC	New England Interstate Water Pollution Control Commission
NH_3	Ammonia
NO_3	Nitrate
NO_2	Nitrite
NTU	Nephelometric Turbidity Units
NO_3-N	Nitrate expressed as mass of the nitrogen
P	Phosphorus
PO_4-P	Phosphate reported as mass of phosphorus
SRP	Soluble reactive phosphorus
TIN	Total inorganic nitrogen
TKN	Total Kjeldahl Nitrogen
TN	Total nitrogen
TP	Total phosphorus
U.S.DA	United States Department of Agriculture
U.S.EPA	United States Environmental Protection Agency

EXECUTIVE SUMMARY

A review of the current scientific literature on nutrient-periphyton relationships was conducted by ENSR for the New England Interstate Water Pollution Control Commission (NEIWPCC) and the United States Environmental Protection Agency (U.S.EPA). The overall goals the project are reviewed in Section 1.0. The results of this literature review are intended to support development of ecoregional nutrient criteria for rivers and streams in New England.

For the literature review described in Section 2.0, papers were identified using two approaches: (1) examination of reference lists in current review articles, EPA guidance documents, and relevant scientific papers; and, (2) a search of electronic databases of scientific literature using key words (see Table 2-1). Based on the review of the scientific literature, forty-six papers were selected as being relevant to the topic subject area. The complete abstract from each paper is provided in Appendix A of this document.

Nutrient levels are only one of the factors that may affect periphyton accrual rates. While evaluating appropriate nutrient levels for control of unacceptable periphyton levels, it is also necessary to consider other potentially limiting factors such as light, temperature, stream velocity, substrate, and grazing. In Section 3.0, these factors that potentially affect periphyton biomass accrual and loss mechanisms were briefly reviewed.

ENSR identified 46 papers that investigated potential relationships between nutrient levels and algal biomass, especially periphyton. These papers were divided into four categories based on the nature of their results and conclusions: (1) studies in which a numerical relationship between algal biomass and nutrient levels was calculated or tested (listed in Table 4-1); (2) studies which presented a quantitative or qualitative relationship (not a regression) between algal biomass and nutrient levels (Table 4-2); (3) studies which found there was no relationship between algal biomass and nutrient levels (Table 4-3); and (4) additional papers generally relevant to the association between nutrients and algal biomass. The results from these studies were further discussed in Section 4.0 as part of the attempt to identify potential useful approaches and predictive relationships.

Section 5.0 presents information on the nutrient-periphyton-impairment linkage that should be considered when developing nutrient criteria. Some potential nutrient thresholds associated with nuisance levels of periphyton were identified from the literature (Table 5-1). Periphyton biomass between 50 to 200 mg/m^2 Chl a or between 20 to 55% of sediment coverage appears to be considered at nuisance levels, with 100 mg/m^2 Chl a considered a median value. EPA's water quality criteria recommendations for EPA sub-ecoregions 59 and 84 for nutrients were substituted into selected regressions and the predicted periphyton levels compared with levels considered potentially harmful to designated uses. Based on those comparisons, it appears that the predicted periphyton levels associated with reference nutrient levels for these sub-ecoregions do not create impairment to designated water uses.

In Section 6.0, the application of the results of the nutrient-periphyton review was evaluated with regard to its implications for the development of ecoregional nutrient criteria for rivers and streams in New England. The main conclusions of the review of the nutrient-periphyton literature were:

- Nutrient control of periphyton biomass is expressed only in the absence of many other non-nutrient limiting factors. Therefore, the applicability of nutrient criteria to streams and rivers may be limited both spatially and temporally;

- Potentially useful predictive relationships between nutrients and periphyton biomass exist and may be the basis for estimating the effect of different levels of nutrients;

- Impairment of designated uses by periphyton has been noted by professional judgment at high biomass concentrations, usually in excess of 100 mg/m^2 Chl a; and

- Estimation of periphyton biomass under current U.S. EPA water quality nutrient recommendation values suggests that those nutrient levels would not result in ready impairment of the waterbodies.

A preliminary evaluation of the literature indicates that there is often a strong linkage between nutrients and periphyton levels and indirectly to potential impairment of water uses. However, this nutrient-designated use impairment linkage needs to be considered in a relatively defined context of applicability to wadeable streams and small rivers. Some rivers lack a periphyton community. Also, in some water bodies, non-nutrient factors control periphyton levels. In both these cases, nutrient criteria developed to prevent excess periphyton biomass may not be appropriate. Nevertheless, consideration of periphyton impacts is likely to be an important component in developing nutrient criteria for rivers and streams in New England.

1.0 INTRODUCTION

This document presents a focused review of the scientific literature for relationships between periphyton biomass and ambient nutrient concentrations in temperate rivers and streams. This review was performed by ENSR as part of the technical support services provided to the New England Interstate Water Pollution Control Commission (NEIWPCC) and the United States Environmental Protection Agency (U.S.EPA) New England in support of the development of ecoregional water quality criteria for nutrients. The results of this literature review will support development of nutrient criteria for rivers and streams in accordance with the U.S.EPA N ational Strategy for the Development of Regional Nutrient Criteria (U.S.EPA 1998).

As part of the development of nutrient criteria, it has been useful to identify relationships between ambient nutrient levels and potential adverse effects or impairments to designated water quality uses. This review has focused on the relationship between nutrients, specifically nitrogen and phosphorus, and levels of attached microalgal growth (i.e., periphyton) ; especially levels of periphyton which may potentially pose an impairment to water quality. In studies of the relationship between nutrient levels and algal biomass in aquatic systems, two general approaches were pursued: (1) an ecosystem approach, where nutrient loading into the aquatic system is related to algal biomass and growth or (2) an approach where ambient nutrient water concentrations are related to algal biomass and growth (Borchardt 1996). While both perspectives are appropriate to the scientific study of algal ecology , the latter approach of seeking relationships between aquatic nutrient concentrations and algal biomass was emphasized in this review. Using measures of ambient nutrient concentrations to establish predictive relationships for rivers and streams is consistent with U.S.EPA's recommended approach es for developing ecoregional nutrient criteria (U.S.EPA 2000a).

This literature review focuses on the relationship between ambient nutrient concentrations and periphyton biomass. High nutrient concentrations may cause additional impairments to rivers and streams that are not discussed in this review. For example, high nutrient concentrations may stimulate high macrophyte biomass in rivers and streams. Additional examples in which excessive nutrient concentrations may harm the ecology and uses of rivers and streams are listed below (U.S.DA 1999; Dodds and Welch 2000; U.S.EPA 2000b):

- Impair use of rivers and streams as drinking water or industrial water sources:
  - High nitrate levels (> 10 mg/L NO_3-N) can cause methemoglobinemia in infants
  - High suspended algae and periphyton levels may clog intake screens or filters in water treatment plants or can slow flow in canals
  - High levels of organic carbon from algal growth may increase production of trihalomethanes during water treatment.
- Directly Impair aquatic life support

- High ammonia concentrations are toxic to aquatic life
- Simulate algal blooms which may release toxi c compounds (e.g., cyanotoxins)
- Excessive growth stimulated by high nutrient levels may lead to extreme daily fluctuations in oxygen concentrations and pH values that can lead to impacts

- Degrade the aesthetic and recreational uses of rivers and streams
  - High periphyton and filamentous algae biomass may be aesthetically unappealing,
  - Aquatic macrophyte levels interfere with swimming and impact fishing activities
  - Nutrient enrichment (eutrophication) may alter plant, invertebrate, and fish community structure

Although some of these harmful outcomes are due to the direct toxicity of nutrients to organisms, most result from nutrient stimulated growth of periphyton, phytoplankton, and macrophytes. Before setting nutrient criteria for rivers, States and Tribes must first consider what levels of nutrient criteria are sufficient to prevent negative effects on waterbodies. Dodds and Welch (2000) compiled a list of established and proposed nutrient criteria or approximate thresholds intended to prevent some of these harmful outcomes (Table 1-1). It should be noted, however, that excessive periphyton growth is only one of the mechanisms by which high nutrient concentrations in streams and rivers may cause impairment, and that algal biomass may not be considered harmful in all circumstances.

The remainder of this report is organized as follows:

- Section 2.0 Description of Data Sources;
- Section 3.0 Factors Influencing Periphyton Biomass in Streams
- Section 4.0 Relationships Between Nutrients and Algal Biomass
- Section 5.0 Nutrient Thresholds for Acceptable Periphyton Biomass
- Section 6.0 Application to Nutrient Criteria
- Section 7.0 References

Copies of abstracts from the papers collected for this review are provided in Appendix A.

Table 1-1 Nutrient Thresholds for Rivers and Streams

Outcome	N (mg/L)	Total P (ug/L)	Comments
Levels recommended to control maximum periphyton below 200 mg/m^2 for 50 days of accrual	0.019 DIN	2 (soluble reactive)	Biggs (2000)
Maximum benthic chlorophyll <200 mg/m^2	3.0 TN	415	Calculated from Dodds et al. (1997)
Mean benthic chlorophyll <50 mg/m^2	0.25 TN	21	Lohman et al. (1992)
Mean benthic chlorophyll <50 mg/m^2	0.47 TN	55	Large data set (Dodds et al. 1997)
Systems with nutrient concentrations in upper ½ of TN distribution	0.9 TN	40	Dodds et al. (1998)
Levels set to control summer phytoplankton		70	Tualatin River, Oregon (R. Burkhart, Oregon Dept. of Environmental Quality, personal communication).
Levels leading to periphyton and macrophyte control	1.0 DIN	< 20 (total dis-solved)	Bow River, Alberta (A. Sosiak, Alberta Environmental Protection, personal communication
Values set by State of Montana and co-operators	0.30 TN	20	Tri-State Implementation Council, Clark Fork Voluntary Nutrient Reduction Program
Planktonic stream chlorophyll <8 µg/L	0.29 TN	42	Calculated from Van Nieuwenhuyse and Jones (1996); chlorophyll level from Organization for Economic Cooperation and Development (OECD, as cited in Rast et al.1989); TN set by Redfield ratio (Harris 1986)
Significant effect on biotic integrity index using invertebrates and fish	1.37 inorganic nitrogen	170	Headwater streams, Ohio (Miltner and Rankin 1998); effects less apparent in larger rivers
Toxicity, aquatic life, chronic	0.005-1 NH_3		Fish data (Russo 1985; Miltner and Rankin 1998)
Toxicity, aquatic life, acute	0.03-5 NH_3		Fish and invertebrate data (Russo 1985)
Toxicity, human	10 NO_3		US national standard

TN = total nitrogen, DIN = dissolved inorganic nitrogen

2.0 DESCRIPTION OF DATA SOURCES

To better understand the relationship between nutrient levels and periphyton biomass, the scientific literature was reviewed for articles that described qualitative or quantitative relationships between nutrients and periphyton in streams and rivers. Given the large potential scope of the subject, emphasis was placed on the following types of systems:

- Streams and rivers in temperate climates likely to resemble aquatic systems found in New England;
- Nutrient-biological responses in natural systems as opposed to artificial stream systems;
- Review articles or studies covering a wide range of flow regimes (small headwater streams and rivers to large rivers); and
- More recent publications (arbitrarily selected as later than 1985).

For the purposes of this literature search, nutrients were defined as nitrogen and phosphorus fractions. Although, periphyton need other nutrients, micronutrients, and cofactors to grow, nitrogen and phosphorus are most likely to limit algae and plant growth in New England rivers and streams.

The emphasis of the literature search was on the relationship between periphyton biomass and nutrient concentrations. During the search, several papers discussing the relationship between suspended algae biomass and nutrient were also identified. These papers are briefly described in this report, but a thorough treatment of this topic is outside of the scope of this literature review.

In the literature review, papers were identified using two approaches: (1) examination of reference lists in current review articles, EPA guidance documents, and relevant scientific papers; and, (2) a search of electronic databases of scientific literature. Reference lists from U.S.EPA's "Nutrient Criteria Technical Guidance Manual, Rivers and Streams" (U.S.EPA 2000b), Biggs' "Eutrophication of streams and rivers: dissolved nutrient-chlorophyll relationships for benthic algae" (Biggs 2000), and Dodds and Welch's "Establishing nutrient criteria in streams" (Dodds and Welch 2000) as well as reference lists in the articles obtained during this literature review were examined for relevant articles. The Cambridge Scientific Abstracts, CSA, database was used to search electronically for current literature. The CSA database includes the following databases: Aquatic Sciences and Fisheries Abstracts (1978-present), Biological Sciences (1982-present), Biology Digest (1989-present), MEDLINE (1989-present), Oceanic Abstracts (1981-present), Plant Science (1994-present) and Water Resources Abstracts (1967-present). The database was searched by looking for keywords in article abstracts, titles, and keyword lists. Some of the keywords searched and the number of records retrieved for each keyword are listed in Table 2-1.

Using both search approaches, forty six papers were selected as being relevant to the topic subject area. The complete abstract from each paper (for which an abstract or summary was available) is reproduced in Appendix A.

Table 2-1 Keywords Used in Electronic Database Search

Search Keywords	Approximate Number of Retrievals
Algal Biomass	1000's
Algal Biomass and Rivers	50
Periphyton	1000's
Periphyton and Rivers	100's
Periphyton and Rivers and Nutrients	50
Periphytic	100's
Periphytic and Rivers	50
New England and periphyton and rivers and nutrients	0
New England and periphyton and river	1
New England and algae and river	1
States (MA, VT, CT, RI, ME, NH) and nutrients	10
Streams and periphyton	100's
Streams and periphyton and nutrients	50

3.0 FACTORS INFLUENCING PERIPHYTON BIOMASS LEVELS IN NEW ENGLAND STREAMS

As part of the development of potential nutrient criteria for rivers and streams, it has been recognized that nutrient levels should be kept below levels that sponsor heavy accumulation of algal mats or periphyton on the waterbody substrate. While evaluating appropriate nutrient levels for control of unacceptable periphyton levels, it is also necessary to consider other potentially limiting factors. Periphyton biomass levels in rivers and streams depend on the balance between biomass accrual and loss mechanisms (Fig. 3-1) (taken from Biggs1996). Nutrient levels are only one of the factors that may affect periphyton accrual rates. In this section, factors that affect periphyton biomass growth and loss will be briefly reviewed. The potential interaction of these forces to create temporal and spatial biomass patterns in rivers will also be briefly discussed. Much of the information presented in this section is discussed in reviews by Biggs (1996) and Borchardt (1996) and elsewhere.

Factors influencing biomass accrual are primarily nutrients, light, temperature, substrate availability, and stream velocity. Nutrients and light are the essential resources which periphyton require for growth, while the other factors can influence biomass accumulation to a variable degree. Non-nutrient controlling factors for periphyton growth are considered below.

The availability of light is perhaps the primary requirement for periphyton growth. Open canopy streams typically maintain periphyton stocks even under oligotrophic conditions since growth can occur under the low but constant nutrient renewal conditions provided by the moving water. On the other hand, light limitation due to forest canopies, shading by dense beds of aquatic macrophytes, or from turbidity in the stream water can severely restrict periphyton levels even in nutrient enriched environments. It is usually light limitation that is considered the limiting factor in determining whether carbon flow is largely autotrophic (i.e., via photosynthetic processes) or heterotrophic (i.e., via decomposition by bacteria and fungi) in headwater streams (Vannote et al. 1980). In addition, numerous experiments involving natural variations and/or artificial manipulations of stream canopy cover has indicated the critical role of light in controlling periphyton growth.

The role of temperature is more indirect in determining periphyton abundance except near the extremes of algal growth (i.e., near freezing (0-1 °C) or near physiological thermal limits (i.e ., 35-40°C). In general, temperature interacts with nutrients and light to stimulate or retard growth by increasing or inhibiting rates of algal metabolism and/or bacterial-mediated recycling of limiting nutrients. However, the seasonal correlation between temperature and light availability often makes it difficult to separate these factors in natural stream systems.

Substrate availability is another potential limiting factor as the periphyton community is typically defined by the areal and not the volumetric dimensions of the stream. In addition, substrate quality or stability are also factors; as evidenced by periphyton abundance on stones, cobble and gravelly environments as opposed to the poor development on sand, clay, and highly organic materials. In general, the substrate composition is largely determined by the stream's flow regime, including stream velocity and scouring potential (see below).

Stream flow characteristics, including the average and peak flows, the variability of stream velocity in the stream channel and over time, and low flow events, are important determinants of the physical structure and biological activity of a stream. With regard to periphyton, stream flow may increase biomass accrual rates by enhancing nutrient and metabolite uptake. Flowing water potentially affects algal nutrient uptake through maintenance of the nutrient concentration gradient existing between the periphyton mat and ambient river water. This gradient exists due to the kinetics of nutrient diffusion from the overlying water into the periphyton mat across the boundary layer, (i.e., the interface between the stream's turbulent and laminar flow zones) existing just above the stream bottom. Increasing nutrient concentrations in stream water can increase diffusive transport across the boundary layer and into algal mats. Increasing stream velocity may also increase nutrient transport to algal cells by thinning the boundary layer, and/or increasing the frequency of turbulent micro-intrusions that penetrate the boundary layer and reach the algal mat.

Stream flow may also influence loss of periphyton biomass. Losses may occur due to scouring, parasitism, disease, and grazing. At some point increasing stream velocity leads to exceedance of a critical velocity and physical disruption and displacement of the algal mat (sloughing) rather than to increased growth rates. The critical velocity at which sloughing occurs depends on several factors, including the physical structure of the periphyton mat itself. Loss of periphyton from stream substrata due to high stream velocities is enhanced by substratum instability (e.g., sandy bottom) and associated abrasion. Losses can also be increased by abrasion of the mat from elevated levels of suspended sediments in the stream water. These factors (i.e., stream velocity and suspended materials load) can greatly accelerate during high velocity flood conditions resulting in mass sloughing or scouring of periphyton. Besides being a major loss mechanism for periphyton, the frequency and intensity of periods of high stream velocity (floods) can influence other accrual and loss variables including: availability of algal propagules for recolonization, nutrient concentrations, water clarity, stream geomorphology/baseflow velocities/substratum size, and density of invertebrate grazers. The frequency of scouring floods often determines the length of the period available for periphyton biomass accrual to occur.

Grazing by invertebrates, such as snails, mayflies, and caddisflies and, to a lesser extent, fish, are biotic mechanisms by which periphyton biomass may be lost. In some cases, grazers control periphyton biomass levels and can offset or lessen potential biomass increases upon nutrient enrichment of the stream. Therefore, water quality concerns that potentially reduce or limit grazer populations (e.g., dissolved toxic metals), can greatly exacerbate the observable effect of high levels of nutrients on periphyton accumulation.

Integration of the growth and loss processes provides an overall model of periphyton biomass accumulation. The interaction of forces favoring periphyton loss and accrual will produce short term and long term temporal patterns of periphyton biomass in rivers and streams. A general conceptual model of short-term periphyton biomass accrual in streams is shown in Fig. 3-2 (taken from Biggs 1996). This pattern typically occurs in natural streams following scouring flood events and reflects the process of re-establishment of the periphyton mat.

Accrual through immigration/colonization and growth dominates in the initial phase of this sequence. After initial settlement, exponential growth limited by light, nutrients, and moderated by temperature follows. The time required to reach peak biomass varies depending on the abundance of colonizing propagules and factors favoring growth, but may be as short as several weeks. Slow colonization rates following a severe flood and slow growth rates may delay attainment of peak biomass for 70-100 days. Paradoxically, peak biomass levels may be reached more quickly in nutrient poor streams than in enriched streams. In nutrient poor streams, the earlier onset of nutrient limitation at the base of the periphyton mat can result in mat degradation and sloughing early in the accrual cycle. In general, higher nutrient levels maintain higher peak biomass levels ; although, this relationship may be influenced by light levels and stream velocities.

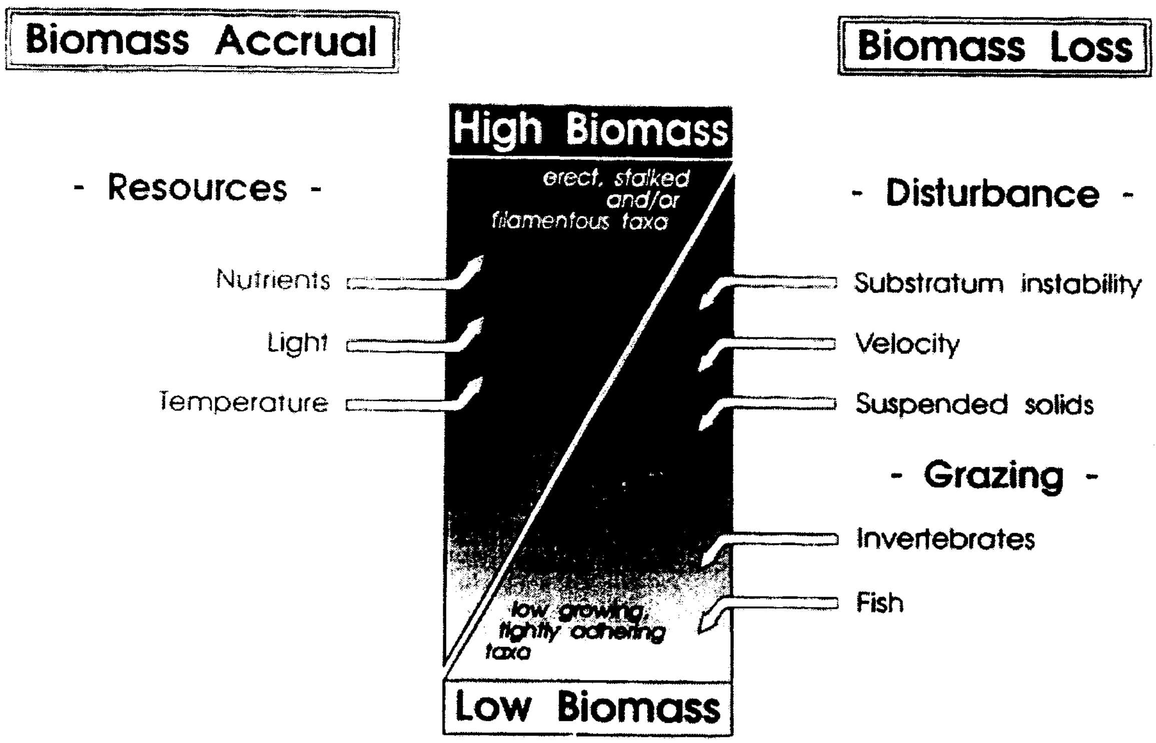
Biomass accrual slows when loss rates approximately balance accrual rates. The carrying capacity is reached when rates of accrual and loss balance. The biomass at this point can vary greatly. Factors probably influencing carrying capacity biomass include rates of metabolite and nutrient diffusion to the base of periphyton mats, substrata type, grazing, hydrodynamic shear stress, and mat tensile strength.

Biggs (1996) presents three main long-term temporal patterns in periphyton biomass that can be found in streams: (1) relatively constant, low biomass systems; (2) systems which experience cycles of accrual and sloughing; and (3) systems which experience seasonal cycles. Relatively constant, low periphyton biomass levels may be found in streams due to frequent disturbances from floods or unstable substratum. Low nutrients, shading, or heavy invertebrate grazing can also result in constant, low biomass levels. Streams in which physical disturbance is infrequent can develop high invertebrate populations which can also maintain low periphyton levels through grazing.

In systems with moderately frequent (e.g., 4-10 weeks) or seasonal floods, biomass levels may fluctuate in cycles of accrual and loss. Extended periods of flow stability allow the accumulation of biomass according to the stages depicted in Fig. 3-2. Also, depletion of invertebrate populations immediately following scouring floods may provide temporary relief from this loss mechanism allowing higher biomass levels to accumulate than would otherwise occur. Seasonal patterns of periphyton biomass result from seasonality of factors which affect biomass growth and loss. Seasonal patterns in periphyton biomass levels may result from: (1) seasonality in disturbance regimes; (2) seasonality in grazer activity (where flood disturbances are rare); or, (3) seasonality in light regimes (where neither disturbances nor grazing is important).

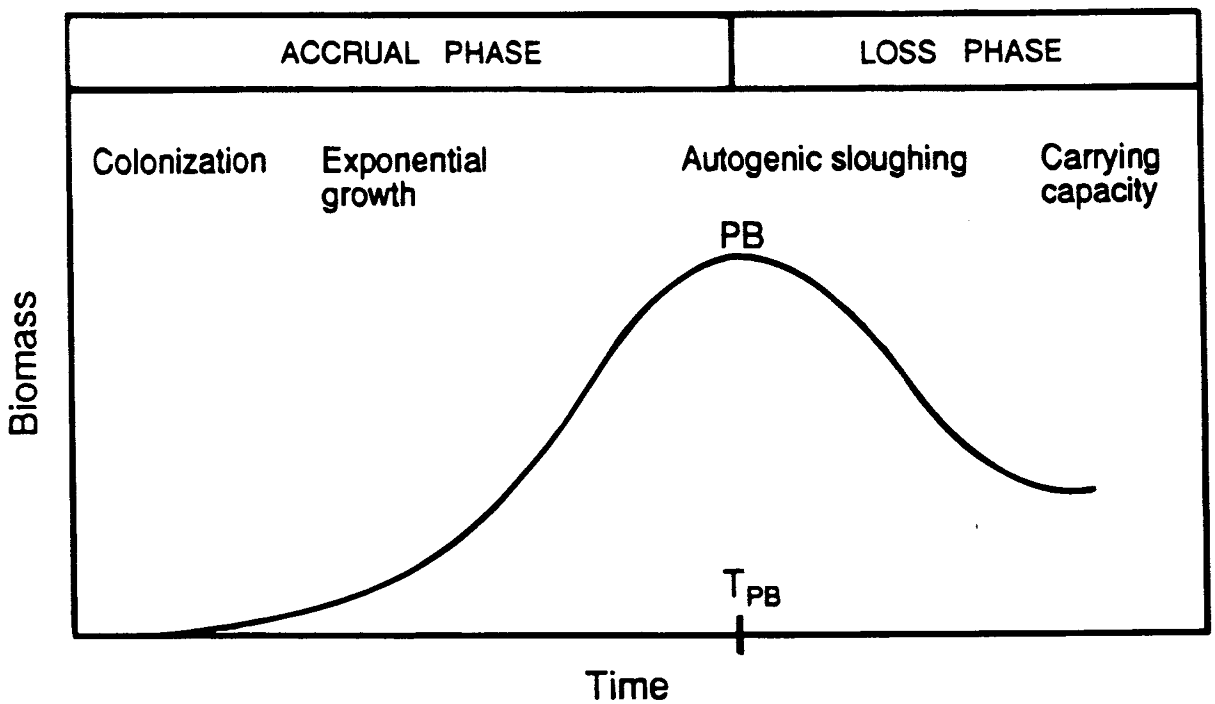
Finally, within streams, variations in the factors affecting periphyton accrual and loss can cause spatial heterogeneity in periphyton biomass levels. Shaded and unshaded portions of the same stream may obviously have very different periphyton biomass levels. Biomass levels can also vary between pool, run, and riffle habitats within the same stream. These differences in biomass levels may reflect differences in shear stress, nutrient transfer, and grazer populations. In nutrient-enriched streams, higher periphyton levels often develop in low-velocity runs and pools rather than in riffles. Sheer stress in riffles restricts the thickness and persistence of the algal mat. In contrast, riffles often have the highest algal biomass levels in unenriched streams. The higher periphyton biomass in riffles of unenriched streams probably results from the increased nutrient mass transfer rates in these areas of higher velocity stream flow and turbulence. Finally, in low velocity runs and pools, high grazer populations may affect periphyton biomass levels more than in higher velocity riffles where current velocity may exclude them.

Figure 3-1 Factors Affecting Periphyton Biomass Accrual and Loss



From Biggs (1996)

Figure 3-2 An Idealized Periphyton Accrual Curve



From Biggs (1996)

4.0 RELATIONSHIPS BETWEEN NUTRIENTS AND ALGAL BIOMASS

Based on the review of the scientific literature, ENSR identified 46 papers that investigated potential relationships between nutrient levels and algal biomass, especially periphyton (see Section 2.0 for details). The 46 papers that were selected were roughly divided into four categories based on the nature of their results and conclusions:

- **Category One:** Studies in which a numerical relationship between algal biomass and nutrient levels was calculated or tested (14 papers concerning periphyton, three papers concerning suspended algae);

- **Category Two**: Studies which present a quantitative or qualitative relationship (not a regression) between algal biomass and nutrient levels (six papers);

- **Category Three**: Studies which found there was no relationship between algal biomass and nutrient levels (11 papers); and,

- **Category Four**: Papers which are relevant to the association between nutrients and algal biomass, but do not directly address their relationship or which discuss their relationship without referring to specific data (13 papers).

The results of the selected studies are summarized in Tables 4-1 through 4-3. It should be noted that the results from some of the papers fell in more than one category and may be listed more than once.

Table 4-1 summarizes the numerical relationships found in papers assigned to category one. The quantitative relationships between nutrients and ecological responses found in these papers were further subdivided into:

- Regressions between periphyton and nutrients using data from natural and artificial systems;

- Process-based models[1] for periphyton as a function of nutrients using data from natural and artificial systems; and,

- Regressions between suspended algae and nutrients based on data from natural systems.

[1] Process-based models attempt to describe mathematically the underlying processes responsible for algal biomass levels in rivers and streams. Process-based models might contain terms which describe algal growth kinetics or losses due to sloughing of algal material.

Table 4-2 summarizes the qualitative relationships between nutrients and algal biomass presented in papers from the second category, while Table 4-3 presents information on studies which found no significant relationship between nutrients and algal biomass in streams and rivers. Papers in category four include a miscellaneous compendium of studies on whether nitrogen or phosphorus is limiting in particular streams and rivers, reviews of the effect of nutrients on algal ecology, approaches to setting nutrient limits, discussions of the suitability of algae as an indicator of environmental degradation, and other topics. Papers in fourth category were identified during the literature review, but they do not represent a comprehensive survey of the diverse topics addressed. Abstracts from those papers,as well as all others listed in Tables 4-1 through 4-3, are reproduced in Appendix A.

In addition to the articles discussing the relationship between nutrients and algal biomass in temperate streams and rivers, we also include papers discussing other important limiting factors discussed in the literature (i.e., the interaction of hydrological disturbance, grazers, light availability, and nutrients on algal biomass). As discussed in Section 3, it is often the interaction of these multiple factors which is key to predicting algal biomass levels in rivers.

4.1 Regressions between Nutrient Levels and Periphyton Biomass in Natural and Artificial Streams and Rivers

As noted earlier, selection preference was given to papers that attempted to elucidate a quantitative relationship between nutrients and periphyton biomass. Empirically-derived regression equations between periphyton biomass and aquatic nutrient levels were the most common form in which quantitative relationships were expressed. Ten selected papers presented or tested regressions between nutrients and periphyton biomass in natural systems, while one paper presented a correlation based on data from an artificial system. The regression expressions often included independent variables besides nutrient concentrations.

Regressions between biomass levels and nutrient concentrations from selected papers are presented in Table 4-1. In some cases, only value of R^2 (estimate of the percentage of variance explained) was reported in the paper and not the entire regression equation. Figures 4-1 and 4- 2 present plots of the data used to derive some of the regression equations cited in Table 4-1.

As noted earlier, emphasis was given to papers conducted in northern temperate stream systems, whenever possible. A variety of geographic locations and stream types were represented in the selected regressions, including New Zealand, Japan, Missouri, and Canada. The selected regression studies also covered a wide range of river sizes, water velocities, and nutrient levels.

Study design often reduced or eliminated the variability of some parameters that could influence or limit algal biomass. In all papers, periphyton biomass was determined by removing algae from stones or gravel from the river bottoms; thus, the effect of different river substrata on periphyton biomass was not considered. Light was generally not considered limited at most sampling sites, although the range of light levels was often not reported. Several authors collected samples only in runs (deep fast water)

(Biggs 2000; Biggs and Close 1989) or riffles (shallow, fast water) (Chetelat et al. 1999). Biggs (2000) sampled runs except in rivers where a large snail population existed in the runs; thus, potential grazer effects were in some part eliminated in this study. Several authors only collected samples during summer months (Lohman et al. 1992; Chetelat et al. 1999), during periods of low flow (Chetelat et al. 1999), or during periods of algal regeneration after scouring flood events (Biggs 1988). Thus, these studies generally selected periods in which maximum algal growth might be expected. Most regressions employed the same measure to quantify periphyton biomass (e.g., mg/m^2 Chl a), but many different independent variables were used to quantify nutrient levels and hydrological factors. The mass of chlorophyll a extracted from periphyton per area of substrata was used to quantify periphyton biomass in almost all studies collected for this literature review. Alternatively, the ash-free dry weight of periphyton biomass was used in papers that did not measure biomass as weight of chlorophyll a. Regressions differed in whether average or maximum periphyton biomass was used in the equation and whether or not the log transform of the dependent variable was used.

Independent variables used in regressions varied widely between papers, but fell into four main categories: (1) nutrient concentrations in the water; (2) surrogates for nutrient loading to the water or nutrient status of the periphyton; (3) factors which might affect periphyton loss through scouring or bed movement; and, (4) environmental factors affecting specific growth rates (Table 4-4). Some studies used mean variable values taken over several sampling periods from each site (Biggs 2000; Biggs et al. 1998a; Lohman et al. 1992; Biggs and Close 1989) while others used values measured at a single time (Aizaki and Sakamoto 1988; Chetelat et al. 1999). Many regressions used log-transformed data for independent and/or dependent variables or raised dependent variable terms to the second or higher orders. In addition, the ranges over which the variables varied differed among studies. Given the differences in study design and regression treatment, meaningful comparisons of the equations in Table 4-1 is challenging.

The squared correlation coefficients (R^2) for only twelve of the regressions in Table 4-1 exceeded 0.70. However, further investigation indicated that regressions that produced correlation coefficients greater than 0.70 typically utilized more than one independent variable or restricted the data used in the regression. That is, regressions with high correlation coefficients between nutrient levels and periphyton biomass typically controlled for many of the factors besides nutrients that can affect algal biomass levels either explicitly in the regression equation or by restricting the data used in the regression.

Biggs and co-workers obtained R^2 values in excess of 0.70 by including terms that quantified the frequency of scouring floods (Biggs 2000; Biggs et al. 1998a; Biggs and Close 1989). Biggs (1988) obtained high correlation coefficients by using temperature and conductivity as independent variables[2]. In this study, conductivity served as a gross water quality surrogate for total nutrient loading to a river and the observed periphyton growth was strongly affected by temperature.

Aizaki and Sakamoto (1988) obtained significant correlations between periphyton biomass and nutrient levels only when restricting their data set to samples collected when the water temperature exceeded 13°C. They hypothesized that only during the summer months (when growth as well as loss of periphyton were maximized) were periphyton biomass levels related to growth rates and thus related to nutrient levels.

Chetelat et al. (1999) obtained a R^2 value of 0.71 for a regression of specific conductivity versus periphyton biomass. In this study, conductivity correlated with nutrient levels and underlying watershed basin geology and negatively correlated with basin size. Chetelat et al's. regression utilized data collected during the summer during low-flow periods. Thus, the effect of scouring floods was controlled for in this study and algal growth rates might be expected to be high. Similarly, Lohman et al. (1992) also controlled for the effect of scouring by excluding periphyton biomass levels less than 2 mg/m^2 Chl a since they were considered to result only from recent flooding. That nutrient concentrations can control periphyton biomass levels if other factors are held constant is shown by the high correlation between phosphate added and periphyton biomass obtained in an artificial stream channel (Bothwell 1989). Ninety three percent of the variation in peak algal biomass level could be explained by the variation in phosphorus added to the system. Although stream water was used in the artificial channels, these experiments controlled for variability in light levels, stream velocity, and substrata, excluded grazers, and occurred over a short time period (2 months).

Three papers attempted to predict periphyton levels based on nutrient levels and other stream variables. In two papers, a model based on equations describing periphyton growth kinetics was used to predict periphyton biomass in streams in Washington (Welch et al. 1989) and New Zealand (Welch et al. 1992). In both papers, the model tended to over-predict the observed periphyton levels. The authors speculate that grazing, shading, and unsuitable substrata in the natural systems may have led to periphyton levels lower than predicted by the model (Welch et al. 1989 ; Welch et al. 1992).

In Biggs et al. (1998a), a regression predicting periphyton biomass based on flood frequency and cellular nitrogen levels in periphyton was used to predict periphyton levels in streams other than those used to develop the regression. Predicted chlorophyll levels were within roughly 20 mg/m^2 Chl a of measured chlorophyll levels except for two sampling locations. At the first location, the authors

[2] Biggs, 1988 regressions are non-linear. In non-linear equations, the partial derivative of the dependent variable with respect to an independent variable is a function of one or more independent variables. For non-linear equations, the correlation coefficient may not equal the fraction of the variance in the dependent variable explained by the independent variable. Calculation of the applicable statistics for non-linear regression equations is outside the scope of this review. We will continue to use the regression coefficient as an estimate of "goodness of fit" for all regression equations given that no better measure is easily available.

believed that high grazing activity led the regression to overpredict periphyton levels. At the second location, the authors could not explain why the model underpredicted periphyton levels.

4.2 Relationships Between Nutrient Levels and Periphyton Biomass Not expressed in Regression Equations

Our literature search identified six papers that presented a relationship between periphyton biomass levels and aquatic nutrient concentrations, but did not quantify that relationship as regression equations that could apply to natural systems. Two papers simply demonstrated that periphyton biomass or biomass accrual rates increased as nutrient levels increased (Burton 19 91; Perrin et al. 1987). The other papers explored how different stream variables affected periphyton response to nutrients. Papers which presented a relationship between periphyton biomass and nutrient limits but which did not quantify this relationship using a regression equation are listed in Table 4-2.

Hill et al. (1992) and Rosemond (1993) showed that light limitation or grazers could moderate or eliminate the observed increase in periphyton biomass with increasing nutrient levels. Biggs (1995) and Horner and Welch (1981) explored the relationship between stream velocity and periphyton response to nutrients. Horner and Welch (1981) found that periphyton accrual rates were highest under moderate average stream velocities (20-50 cm/s), moderate peak velocities, and moderate to high phosphorus levels. Accrual rates were lowest under high average velocities (5-80 cm/s), high peak velocities, and low nutrient levels.

Biggs (1995) found that the response of periphyton biomass to changes in stream velocity varied with the stream's "enrichment group". "Enrichment group" categorization was based on land-use and underlying geology and correlated with cellular nitrogen concentrations in periphyton. In high and moderate enrichment groups, increasing the annual 80th percentile mean cross-section velocity correlated with a decrease in periphyton biomass. In the low enrichment group, changing the 80 th percentile stream velocity had no effect on periphyton biomass.

4.3 Studies Which found no Relationship Between Nutrient Levels and Periphyton Biomass

Eleven papers of those selected by the literature search found no relationship between aquatic nutrient concentrations and periphyton biomass levels. These papers are listed in Table 4-3. The papers presented several different hypotheses why nutrient concentrations did not correlate with periphyton biomass levels.

In two papers, the authors believed ambient nutrient levels in the rivers were already so high that periphyton response to nutrients had reached a maximum and nutrients were no longer limiting growth rates (Munn et al. 1989; Wharfe et al. 1984). Addition of further nutrients did not stimulate further biomass production. In four papers, light availability or grazers were believed to control or strongly affect periphyton biomass levels such that no correlation between periphyton biomass and nutrient levels was observed (Bourassa and Cataneo 1998; Lowe et al. 1986; Rosemond 1994; and Welch et al. 1988). Humphrey and Stevenson (1992) found that brief increases in nutrient levels coinciding with below-scouring increases in water velocity raised cellular phosphorus levels but did not increase algal biomass. They hypothesized that in nutrient-rich streams, an increase in periphyton biomass could be observed under similar circumstances.

In several other papers, factors that are not clearly identified appear to control or affect periphyton levels, preventing a simple dependence on nutrient concentrations. Aizaki & Sakamoto (1988) found no relationship between periphyton biomass and nutrient concentrations when using winter or annual data. The authors hypothesized that during winter, nutrient-limited growth does not control biomass levels. Jones et al. (1984) found no relationship between periphyton levels and nutrient concentrations in Ozark streams. They did find a relationship between suspended algae levels and nutrient concentrations, but only during periods of low flow. Leland (1995) found algal biomass correlated with composition and density of the riparian vegetation in the Yakima River basin, but not with measured chemical-constituent concentrations. However, elevated biomass occurred only in major agricultural drains with specific conductivity levels greater than 500 uS/cm and inorganic nitrogen levels greater than 2.9 mg-N/l.

4.4 Suspended Algae

Three papers presented regressions between suspended algal biomass (i.e., combination of detached periphyton and "true" phytoplankton) levels and nutrient concentrations in the water. Two studies considered data from a variety of rivers and streams while the third, Yang et al. (1997) studied algal biomass levels along a single lake-fed stream. The hypotheses and results of these papers reflected this difference in approach and river systems under study.

Jones et al. (1984) and Van Nieuwenhuyse and Jones (1996) studied suspended algal biomass levels in a number of rivers and streams. Jones et al. (1984) assumed and Van Nieuwenhuyse and Jones (1996) considered the possibility that suspended algae originated as periphyton that had been detached or sloughed from river substrata. Van Nieuwenhuyse and Jones (1996) used only data collected during the summer while Jones et al. (1984) segregated their data by season.

Jones et al. (1984) found for spring data a positive correlation between watershed area and suspended algal biomass. Jones et al. (1984) hypothesized that during the spring, the forest canopy did not limit light, stream flows were high and nutrient levels were fairly homogeneous. These authors felt that, under these conditions, growth and detachment of periphyton per unit area of streambed would be similar along stream sections and between streams. Going downstream in a watershed, the streambed area increases at a faster rate than watershed area, meaning that the area of the riverbed which contributed suspended periphyton increased faster than the volume of water in which the cells were suspended. Accordingly, suspended algae, originating as periphyton detached during the high flows of spring, increased in concentration during downstream transport and the levels of suspended algae correlated with watershed area.

Van Nieuwenhuyse and Jones (1996) also hypothesized that physical factors affect levels of suspended algae in rivers. They found that the ratio of periphyton biomass to total phosphorus increased with stream catchment area. Van Nieuwenhuyse and Jones (1996) proposed that the effect of catchment area on Chl a:TP ratios was due to the decrease in mean hydraulic flushing rate with increasing catchment area. Decreasing the flushing (washout) rate would allow suspended periphyton more time to grow, thus increasing their biomass. Alternatively, decreasing flushing rates would provide more time for dislodged periphyton to accumulate in the water column. Either way, Van Nieuwenhuyse and Jones (1996), concluded, Chl a:TP should increase with catchment size because the average loss (washout) rate a stream imposes on sestonic algal biomass generally decreases with catchment size.

Nutrient levels were also found to correlate with levels of suspended algae. Van Nieuwenhuyse and Jones (1996) found a strong correlation between total phosphorus levels and suspended algal biomass. The authors suggested that phosphorus may either stimulate growth of suspended algae directly or stimulate growth of benthic algae which is then released from the substrata into the water column. Jones et al. (1984) found that during most of the summer and fall data examined, it was nutrients, not watershed area, that were largely responsible for the difference in suspended algal biomass. Jones et al. (1984) believed that differing canopie s, flow levels, and varying nutrient levels produced diversity in algal production among and within streams during summer and fall. They hypothesized that production and loss of periphyton was no longer constant along and between rivers in the summer and fall. Watershed area no longer explained differences in algal biomass, but nutrients had a stronger effect.

Yang et al. (1997) focused on the development of suspended algal biomass and changes in algal species along the length of a single lake-fed lowland river in Canada. They found that algal biomass increased with nitrogen concentrations and with the "age" of water as reflected in the downstream water travel distance. The increase in algal biomass with down stream travel time was due largely to an increase in the proportional amount of morphometrically large algal species with travel distance. Taxonomic speciation of the suspended algae assemblage found that the suspended algae were largely of planktonic origin while the benthic algae dominated only in shallow or fast-flowing areas of the river. The authors hypothesized that increased travel-time as well as increased nutrient concentrations led to the dominance of large algal species and hence higher algal biomass.

4.5 Summary

The papers selected from the literature review provide a representative spectrum of the range of results seen in periphyton ecology and the highly variable influence of physical, chemical, and biological factors on periphyton biomass accumulation. A review of these papers supports the general growth model presented in Section 3, where factors besides nutrient levels are capable of influencing and controlling periphyton biomass levels. High correlation coefficients resulted only when factors other than nutrients were added to the regression or when study design controlled for variables that could affect periphyton biomass levels. Many studies found that no correlation existed between nutrient concentrations and periphyton biomass. The different independent variables used in the regressions and various methods of data treatment make meaningful comparison of these equations challenging. This also suggests that development of nutrient criteria based on periphyton growth will also be challenging.

Fewer papers were found exploring the relationship between suspended algae and nutrient concentrations in rivers. As with papers exploring periphyton nutrient relationships, nutrients could explain a part of the variability in suspended algal biomass levels, but other variables such as flow, light levels, catchment size or travel-time were also important. It is possible that the source of suspended algae, release of periphyton or growth of planktonic species, varies between and along streams. Differing mechanisms may control suspended algae levels depending on the season and on the source of the algal cells.

Table 4-1 Papers Presenting Numerical Relationships between Nutrients and Algal Biomass in Rivers and Streams

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Relationship	R^2	Variable Ranges in Regressions / Notes
Periphyton vs. Nutrients in Natural Systems - Regressions										
Aizaki & Sakamoto 1988	Kanto region of Japan	small streams to large rivers	25 sites in 12 rivers	algae sampled from gravel	sites < 50 cm deep	50-100 cm/s	1981-1983, all seasons	Chl vs. TP	0.66	n = 10-11; TP: 2-1909; Chl 4-1115
								Chl vs. PO_4-P	0.81	PO4-P: 2 – 1286
								Chl vs. TN	0.76	TN: 320-17010
								Chl vs. TIN	0.83	TIN: 56-12421 Regressions only include data where temperature > 13°C. Parameter ranges are for data at all temperatures.
Biggs 2000	New Zealand hill-country watersheds	streams & rivers	30 sites from 25 streams	algae usually sampled from coarse gravel & cobbles	not light limited	generally mod. to swift flowing, sites at runs	≥ 1 year	Log(mean Chl) = 1.355Log(Da)-0.888	0.40	Mean & max refer to monthly sample results. For chlorophyll values, a geometric mean was used. n = 30 for all regressions
								Log(mean Chl) = 0.483Log(SIN)+0.109	0.12	
								Log(mean Chl) = 0.697Log(SRP)+0.468	0.23	SRP : 1.3 - 31.6
								Log(mean Chl) = 1.245Log(Da)+0.284Log(SIN)-1.229	0.44	SIN : 6.2 - 232
								Log(mean Chl) = 1.152Log(Da)+0.462Log(SRP)-0.926	0.49	Mean Chl : 0.73 - 281
								Log(max Chl) = 5.223Log(Da)-1.170(Log(Da))^2-2.886	0.62	Max Chl : 9.1 - 1396
								Log(max Chl) = 0.688Log(SIN)+0.711	0.33	Da : 10 - 183
								Log(max Chl) = 0.797Log(SRP)+1.400	0.30	
								Log(max Chl) = 4.285Log(Da)-0.929(Log(Da))^2+0.504Log(SIN)-2.946	0.74	
								Log(max Chl) = 4.716Log(Da)-1.076(Log(Da))^2+0.494Log(SRP)-2.714	0.72	

Abreviations and units listed at end of table

Table 4-1 Papers Presenting Numerical Relationships between Nutrients and Algal Biomass in Rivers and Streams (cont.)

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Relationship	R^2	Variable Ranges in Regressions / Notes
Periphyton vs. Nutrients in Natural Systems - Regressions (cont.)										
Biggs 1988	New Zealand	foothill-fed rivers, flows < 30 to ~100 m3/s	103 rivers	coarse gravel & cobbles	not light limited	NA	NA	AFDW = $(8.15Log(C) - 4.23)^2$; n = 146	0.51	Data only from periphyton accrual stage;
								AFDW = $(0.0079a+ 2.03Log(C) +0.0467T 1.39)^4$; n = 88	0.76	Exponent on regressions may be an editing mistake
								AFDW = $(0.355Log(1/Q)+0.0101a+ 0.684Log(C) +0.0254T-0.611)^4$; n = 66	0.79	C: ~3 - 100; AFDW: ~1 - 150, ranges for other parameters NA
Biggs et al. 1998a	Data for regression from Biggs and Thomsen (1995)							Ln (Chl) = 1.053 - 0.67[flood frequency]+0.764[% cellular N]; n=15	0.86	Chl refers to mean biomass; flood frequency = ave. freq. per year of velocities exceeding 1 m/s
Biggs et al. 1998b	Kakanui River, South Island, New Zealand	5th and 6th order	6 sites on 1 river	cobbles and gravel	headwater sites have some shading, otherwise not light limited	19-69 cm/s	2 years	Regression from Briggs 1998b used as predictive model; n = 12; geometric mean monthly Chl: 2.0 - 91.2; Flood frequency: 1.5 - 11. One data point excluded from regression of predicted vs. observed biomass levels.	pred. vs. obs. R^2 = 0.52	Predicted vs. observed Chl levels match within roughly 20 mg/m^2 except for 2 pts. For 1 pt., model over-estimates biomass at site of high grazer activity. This pt excluded from regression. At second pt., model under-predicts biomass for no known reason.
Chetelat et al. 1999	lowland rivers in southern Ontario and western Quebec	drainage basins from 400 to 9.1×10^4 km^2	33 sites on 13 rivers	primarily rock	usually not light limited	10-107 cm/s, sites at riffles	June-Aug. in 1993, 1995 or 1996 during low flow. One sampling even per site.	Log(Chl)=0.002(Cond)+1.134; n=25 Log(Chl) = 0.905Log(TP)+0.490; n=33 Log(Chl) = 0.984Log(TN)-0.935; n=30	0.71 0.56 0.50	Cond: 65-723; TP: 6-130 TN : 179-2873 Chl : 9-470

Abreviations and units listed at end of table

Table 4-1 Papers Presenting Numerical Relationships between Nutrients and Algal Biomass in Rivers and Streams (cont.)

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Relationship	R^2	Variable Ranges in Regressions / Notes
Periphyton vs. Nutrients in Natural Systems - Regressions (cont.)										
Dodds et al. 1997	North America, New Zealand, Europe	variable	> 200 sites	na	na	na	year round, mainly summer	Log (mean Chl) = 0.92178Log(TP)-0.16468(log(TP))^2+0.37408log(TN)-0.4285	0.43	Over 20 regressions calculated. Four with highest R^2 listed.
								Log(mean Chl) = 2.82630Log(TN)-0.431247(log(TN))^2+0.25464Log(TP)-3.22360	0.43	
								Log(max Chl) = 1.10067Log(TP)-0.19286(Log(TP))^2+0.3129Log(TN) + 0.00652	0.37	
								Log(max Chl) = 2.78572Log(TN)-0.43340(log(TN))^2+0.30568Log(TP)-2.70217	0.35	
Lohman et al. 1992	Northern Ozarks, MO	~ 2nd to 4th order streams	22 sites on 12 streams	periphyton collected from rocks	NA	NA	March-Nov., 1985 & 1986	Chl = 76.9Log(TN) - 155.8; 1985	0.58	All variables in regressions are mean annual values. Chl < 2 excluded.
								Chl = 69.3Log(TN)-116.7;n = 22; 1986 Chl = 39.9Log(TP) - 18.1;n = 22; 1985	0.60 0.47	Mean annual TN : 148 - 9188; Mean annual TP : 6 - 3264;
								Chl = 41.1Log(TP)-4.1;n = 22; 1986	0.60	Mean annual Chl : 10.3 - 216.7. Chl accrual rates varied with TP
Biggs & Close 1989	New Zealand	mean annual flows 0.94-169 m^3/s	9 rivers	fine gravel to large cobbles	NA, sites < 1 m deep	15-80 cm/s, sites in runs	13 months	mean Chl vs. mean SRP + mean TIN	0.52 0.58	R^2 reflects cumulative multiple linear regression. Mean refers to geometric mean. Mean Chl: 4.6-73; mean SRP: 1.3-68
								mean Chl vs. mean SRP + mean time in flood (%) + mean TIN + mean total suspended solids + mean flow + mean rock size	0.52 0.59 0.69 0.89 0.90 0.94	Mean days in flood: 0-44%. Mean TSS: 1.6-12.8. Mean flow: 169-0.94 m^3/s. Mean rock size:0.026 -0.062 m^2 surface area available for colonization
Biggs & Close 1989	New Zealand	mean annual flows 0.94-169 m^3/s	9 rivers	fine gravel to large cobbles	NA, sites < 1 m deep	15-80 cm/s, sites in runs	13 months	Mean Chl = 47.6Log(mean TP) - 31.9; n=9	0.57	Mean TP: 6.2-85; Equation calculated by Lohman et al, 1992

Abreviations and units listed at end of table

Table 4-1 Papers Presenting Numerical Relationships between Nutrients and Algal Biomass in Rivers and Streams (cont.)

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Relationship	R^2	Variable Ranges in Regressions / Notes
Periphyton vs. Nutrients in Natural Systems - Process-Based Models										
Welch et al. 1989	Spokane River + streams near Seattle, WA	streams, river	sites on Spokane River + 6 other streams	NA	not light limited	NA		$Chl = (B_{max} - (K_2V^{theta}) / [K_1uL(k_f+K_{fo})]) \times [1-exp(-K_1uL(k_f+K_{fo})t)]$; K_1 is a function of P	---	Does not account for grazing; In comparisons to real data, model overestimated number of streams with nuisance biomass levels
Welch et al. 1989	---	---	---	---	---	---	---	$D_c=Qr(SRP_i-SRP_c) / [(P/Chl\ a\text{-}day)B_nTrW10^3]$	---	Predictions not compared with real data
Welch et al. 1992	New Zealand	depth: 0.3-0.45 m; width: 2.3 - 55 m	18 sites on 7 streams	bedrock, boulders, cobbles, large gravel	variable	23 - 80 cm/s	February	Model not listed in article, appears similar or identical in formulation to Welch et al., 1989. Considers SRP limited growth, temperature, scouring, article does not mention if light level considered, does not account for grazing. SRP: 2-2690; Chl:4-1262	----	Ratio of average obs. to predicted biomass = 0.35 ± 0.44. Authors believe grazers, shading, and unsuitable substrata kept obs. periphyton biomass lower than expected based on P levels.
Periphyton vs. Nutrients in Artificial Systems - Regressions										
Bothwell 1989	South Tompson River, British Columbia	2 m x 19 cm artificial channels fed river water	5 channels per study	styrofoam	not light limited	50 cm/s	~ 2 months	Chl (peak) = 44.1Log(P added) + 247.4	0.93	P added = P added diluted by volume of channel, does not consider algal uptake. P added: 0-100 ug/L; Chl : ~1 to 350
Periphyton vs. Nutrients in Artificial Systems - Process-Based Models										
Walton et al. 1995	Seattle, WA	1 m x 20 cm artificial channels fed pond water	12 channels	cobbles	not light limited	20 cm/s	28-32 days	$Chl = [K_1uL(k_f + k_{fo})B_{max} - (K_2V^{theta})] / [(K_1uL(k_f+K_{fo})+K_3) \times (1-exp(-K_1uL(k_f+K_{fo})+K_3)t)]$	---	Does not account for increase in grazers with increasing algal productivity as might be expected in natural systems.

Abreviations and units listed at end of table

Table 4-1 Papers Presenting Numerical Relationships between Nutrients and Algal Biomass in Rivers and Streams (cont.)

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Relationship	R^2	Variable Ranges in Regressions / Notes
Suspended Algae vs. Nutrients in Natural Systems - Regressions										
Jones et al. 1984	MO Ozark Plateau in south-central MO.	> 3rd order	12 sites on 8 streams	cobble	not light limited	NA	June-Dec. 1978 & Mar. - Sept. 1979	Log(mean Phy) = -0.09 + 0.39log(mean TP); n =36	0.41	Means for each site in summer and fall 1978-79 (low flow). Spring Phy not correlated with nutrients, but was correlated with watershed area.
								Log(mean Phy) = 0.1 + 0.39log(mean TP) + 0.34log(mean TN); n=36	0.53	mean suspended Phy: 1.7 - 14.4; mean TP: 6.8 - 184.5; mean TN: 478 - 2782
Van Nieuwenhuyse & Jones 1996	primarily North America and Europe	drainage basins from 1-5. x105 km^2	116 streams and rivers	NA	not light limited	variable	NA	Log(Phy) = -1.65+1.99Log(TP)-0.28(Log(TP))^2	0.67	Catchment Area (Ac): 1-5. x10^5 km^2
								Log(Phy) = -1.92+1.96Log(TP)-0.30(Log(TP))2+0.12Log(Ac)	0.73	TP : 5-1030; Phy: 0.4-170
Yang, et al. 1997	Southern Ontario, Canada	ave. annual discharge 38.9 m^3/s	7 sites on Rideau River	NA	Secchi depth: 1-4 m	NA	July - Sept., 1993	total biomass vs. total nitrogen; polynomial regression	0.76	Increase in biomass due to increase in # of large plankton; no correlation with TP or SRP; TN range: 428-837;
								total biomass vs. travel distance; polynomial regression	0.43	biomass range: approx. 0.5 - 8 g/m^3; distance traveled range: 0 90 km

Abbreviations in Table 1
a: accrual time since last flood (days)
Ac: catchment size (km^2)
AFDW: ash free dry weight (g/m^2)
C: water conductivity (mS/m)
Chl: periphyton chlorophyll a biomass (mg/m^2)
Cond: water conductivity (uS/cm)
Da: interval between flow > 3 times median flow (days)
IN: inorganic nitrogen (ammonia + nitrate + nitrite) (ug/L)
N: nitrogen, form unspecified (ug/L)
NA: information not available
P: phosphorus, form unspecified (ug/L)
Phy: phytoplankton biomass (mg/m^3)

Abbreviations in Table 1 (cont.)
SIN: soluble inorganic nitrogen (ug/L)
SRP: soluble reactive phosphorus (ug/L)
T: water temperature (C)
TN: total nitrogen (ug/L)
TIN: total inorganic nitrogen (ug/L)
TP: total phosphorus (ug/L)
TSS: total suspended solids (mg/l)

Abbreviations in Table 1 from Welch et al., 1989 and Walton et al., 1995
B: periphyton biomass
B_{max}: maximum areal periphyton biomass that can be sustained in a mat
B_n: nuisance biomass threshold

PO_4-P: phosphate as P (ug/L)

Q: flow (m^3/s)

D: diffusion coefficient

D_c: length of river for which periphyton biomass exceeds SRP_c (km)

Table 4-1 Papers Presenting Numerical Relationships between Nutrients and Algal Biomass in Rivers and Streams

Abbreviations in Table 1 from Welch et al., 1989 and Walton et al., 1995 (cont.)

K_1: growth coefficient, function of SRP
K_2: scour coefficient
K_3: grazing coefficient
K_{fo}: non-turbulent mass transfer coefficient
K_f: turbulent mass transfer coefficient
K_s: phosphorus half-saturation constant
L: light reduction factor
P/chl a-day: average uptake rate by periphyton mat per day
Q: daily flow
r: recycle rate
SRP_i: influent SRP concentration
SRP_c: SRP producing threshold nuisance biomass (B_n) in growth period
t: growth period
Tr: factor for trophic (consumer) retention
Theta: velocity exponent
u: uptake rate of SRP based on Michaelis-Menton kinetics
u_{max}: maximum growth rate
V: stream velocity
W: average stream width

Table 4-2 Papers Presenting Quantitative and Qualitative Relationships (not regressions) Between Nutrients and Algal Biomass in Rivers and Streams

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Notes
Biggs 1995	New Zealand	median flow 0.2 - 43.3 m^3/s	16 stream sites in 12 catchments	Periphyton collected from stones	na	33-84 cm/s	sampled once monthly for year	The sites were classified into three enrichment groups (high, moderate, low) based on land use and underlying geology. The relationship between periphyton biomass and annual 80th percentile mean cross-section velocity differed depending on site enrichment group. A stepwise multiple regression on the full data set identified that the frequency of floods, the proportion of catchments in high intensity agricultural land use, and the proportion of the catchment in alkaline rocks as the most significant factors explaining variation in mean biomass among sites.
Burton et al. 1991	Michigan Upper Peninsula	Two 4th order rivers	na	nutrient enriched artificial substrates	sunny	na	28 days in late summer/early fall	Addition of nitrogen inhibited algal growth compared to controls. Addition of phosphorus stimulated algal growth in both rivers, but a larger biomass accumulated on the phosphorus-enriched artificial substrate in the Peshekee River than in the Ford River. The biggest algal response to nutrient addition was seen in the Ford River, however, when both nitrogen and phosphorus were added to the artificial substrate.
Hill et al. 1992	Tennessee	2nd order	4	artificial substrate	not limited	7.6 cm/s	3 weeks in Autumn	Phosphate and nitrate were added to channels in a stream to increase nutrient levels to 3-4 times ambient levels. Nutrients increased periphyton biomass on artificial substrates accessible and inaccessible to invertebrate grazers; however, periphyton biomass increased the most on artificial substrates in nutrient enriched streams which were protected from grazing.
Horner & Welch 1981	Washington	1st to 4th order	12 sites in 6 streams	rocks placed in streams	na	0.3-137.2 cm/s	2 - 11 wk experiments July-Aug and Aug to Sep.	Accrual of periphyton was analyzed as a function of stream velocity and nutrient levels. Highest rates of biomass accrual were found under moderate average velocities (20-50 cm/s), moderate peak velocities, moderate to high PO_4-P levels, and moderate to high SRP levels. Lowers biomass accrual rates were found in cases with high average velocity (50-80 cm/s), high peak velocity, low PO_4-P levels, low SRP levels, and low NO_3-N levels. The authors present regressions for Ln Chl a measured after eleven weeks as a function of time, stream velocity, and phosphate levels.

Table 4-2 Papers Presenting Quantitative and Qualitative Relationships (not regressions) Between Nutrients and Algal Biomass in Rivers and Streams (cont.)

Reference	Location	Stream / River Size	# sites	Substrata	Light Level	Water Velocity	Duration / Season of Study	Notes
Rosemond 1993	Tennessee	side-stream, artificial flow-through channel	8 treatments, 2 channels each treatment	unglazed tiles	variable	10-15 cm/s	seven wks, July-Sep.	The author tested for the effects of nutrients (+NU: N + P added, -NU: ambient N + P levels), irradiance (+L :light added, -L: shaded), and snail grazing (+G: snails added, -G: no snails) on a benthic algal community. Experiments were performed with these three factors in all possible combinations (8 different treatments). Periphyton biomass on unglazed tiles was between approximately 10 –30 mg Chl/m^2 for all treatments except the –G,+L,+NU treatment which resulted in biomass levels of approximately 70 mg Chl/m^2. Only the biomass level in the –G,+L,+NU treatment was significantly different than any other treatment.
Perrin et al. 1987	British Columbia	Mean summer discharge 1.6 m^3/s	4 sites in 1 river	styrofoam	na	40 cm/s	five 2-4 week periods, April - Sep.	Periphyton accumulation rates on styrofoam artificial substrates were examined in reaches of the Keogh River, British Columbia, following additions of inorganic fertilizer. Nutrient additions increased biomass accrual rates by more than order of magnitude.

Table 4-3 Papers Which Found No Relationship between Nutrients and Algal Biomass in Rivers and Streams

Reference	Location	Stream / River Size	# sites	Sub-strata	Light Level	Water Velocity	Duration / Season of Study	Phosphorus Range (ug/l)	Nitrogen Range (ug/l)	Algae Range (Chl mg/m^2)	Notes
Aizaki & Sakamoto, 1988	Kanto region of Japan	small streams to large rivers	25 sites in 12 rivers	NA	sites < 50 cm deep	50-100 cm/s	1981-1983	TP: 2-1909; PO_4-P: 2 – 1286	TN: 320-17010; TIN: 56-12421	Chl 4-1115	Significant correlations between nutrients and algal biomass observed if only data from temperature > 13°C is included in regression.
Bourassa & Cattaneo, 1998	lower Laurentian mountains of Quebec	2nd and 3rd order	12 streams	boulders and cobbles	variable	11-46 cm/s	July - Aug., 1994	TP: 5-54	TN: 231 - 996	5.1 - 54.6	Only velocity and depth were correlated with Chl (R^2 = 0.1 and 0.2); grazers believed to control periphyton biomass at least in summer during low flows
Humphrey and Stevenson, 1992	Wilson Creek near Louisville, KY	3 x 0.1 m vinyl gutter fed from Wilson Creek	24 gutters	unglazed tiles	NA	10 cm/s with 20 cm/s spates	9 weeks	ambient 2.5-5.0; during spate 30 PO_4-P	ambient 95-200; during spate 600 NO_3-N	---	Spates lasted 24 hrs with increased nutrient addition during first 12 hrs. Study was designed to simulate conditions in real streams. Nutrients had no affect on periphyton biomass up to 6 days after spate.
Jones et al., 1984	Missouri Ozark Plateau in south-central MO.	> 3rd order	12 sites on 8 streams	cobble	unshaded	NA	June-Dec. 1978 & Mar. - Sept. 1979	TP: 6.8 - 184.5	TN: 487 - 8112	1.8 - 392	Using data within seasons, no correlation between mean benthic algal biomass by site and mean nutrient levels, current, discharge, nutrient loading, gradient of streambed, and watershed area in single or multiple regression was significant ($P > 0.05$).
Leland, 1995	Yakima River Basin, WA	1st order to major river	34 stream reaches	NA	variable	variable	Oct - Nov.	TP: approx. 4 - 470	NO_3 + NO_2: approx. 5 - 4760	10 - 100	AFDM correlated with composition and density of riparian vegetation but not with levels of N or P. Chl was unrelated to any environmental attribute. Elevated amounts of AFDM (>500 g/m^2 AFDM) occurred only in major agricultural drains of the middle and lower valleys of the Columbia Plateau (specific conductance > 500 uS/cm at 25C and inorganic N > 2.9 mg-N/L).

Table 4-3 Papers Which Found No Relationship between Nutrients and Algal Biomass in Rivers and Streams (cont.)

Reference	Location	Stream / River Size	# sites	Sub-strata	Light Level	Water Velocity	Duration / Season of Study	Phosphorus Range (ug/l)	Nitrogen Range (ug/l)	Algae Range (Chl mg/m^2)	Notes
Lowe et al., 1986	Appalachian Mts., NC	2nd order	2 streams: one forested & one clear-cut	nutrient amended agar	variable	NA	April - May or April - June	ambient PO_4-P: 2	ambient NO_3-N: 2-4	---	Periphyton growth on artificial substrata enriched and not enriched in N, P, Ca examined in clear-cut and forested streams; periphyton biomass did not respond to nutrients in either stream; sunlight appeared to control periphyton biomass in forested stream
Munn et al., 1989	east-central Illinois	approx. 2nd to 5th order	7 streams	nutrient amended agar	NA	---	5 - 9 days	ambient SRP: 330 - 2900	ambient NO_3: 1800 - 5800	Accrual rate: 0.24-1.5 mg/m^2-day	Growth of periphyton on nutrient enriched artificial substrate was independent of added nutrients due to high ambient nutrient levels in streams. Periphyton accrual rate correlated with temperature and turbidity (R^2=0.91).
Rosemond, 1994	Oak Ridge, TN	1st order	4 sites on one stream	cobble, gravel, bedrock	variable, shaded during growing season	NA	2 years	SRP: approx. 3.5-5.2	TIN: approx. 0 - 50	approx. 15 - 22	Grazers believed to control periphyton biomass
Sumner & Fisher, 1979	Fort River, Pelham hills, central MA	105 km^2 watershed	8 sites on Fort River	cobble, mixed cobble, sand, sand silt	variable	12-18	17 months	PO_4-P: ave. 25	NO_3-N usually < 200	monthly mean: 21.2-90.8	Study not designed to test N/P - Chl relationships. Authors believe nutrients do not control observed periphyton variability since nutrient variability has not been observed in past years.

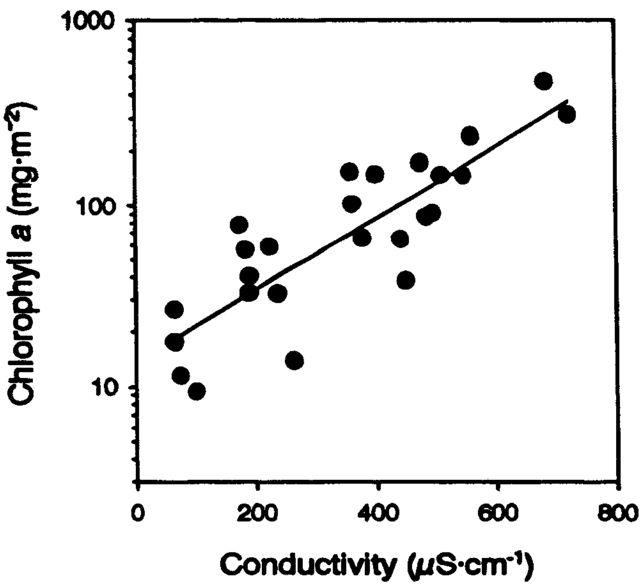
Table 4-3 Papers Which Found No Relationship between Nutrients and Algal Biomass in Rivers and Streams (cont.)

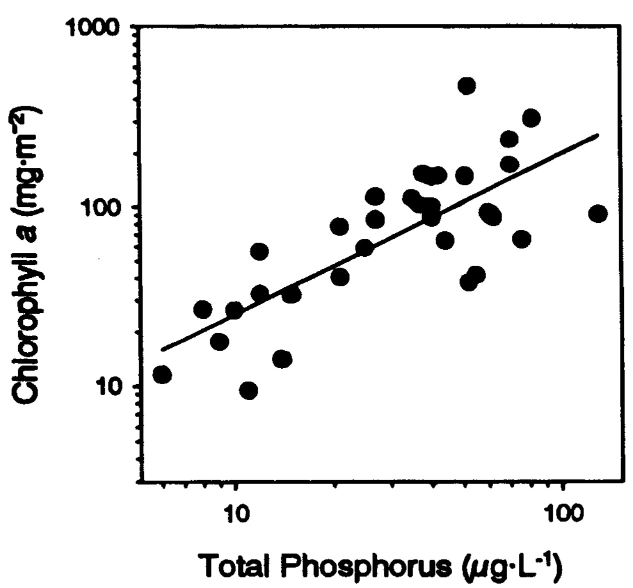
Reference	Location	Stream / River Size	# sites	Sub-strata	Light Level	Water Velocity	Duration / Season of Study	Phosphorus Range (ug/l)	Nitrogen Range (ug/l)	Algae Range (Chl mg/m^2)	Notes
Welch et al., 1988	western WA	NA	6 streams	stony	unshaded except one site	5 - 75 cms/s	April - Sept., 1984	stream mean SRP: 5 - 51	stream mean nitrate + nitrite: 144 - 1768	stream mean: 23 - 166; max: 54 - 805	No relationship between SRP and max or mean Chl or between nitrate+nitirite and max or mean Chl. Chl did increase with stream velocity. Authors believe streams not supporting biomass levels consistent with high SRP concentrations may have been limited by light or grazers. Study also present 12 SRP & Chl pairs from US and Sweden measuring SRP & peak summer biomass on one occasion. R^2=0.30 (calc. by ENSR).
Wharfe et al., 1984	River Great Stout, Kent, England	6-18 m wide, 15-100 cm deep	5	gravel, fine deposits	unshaded	NA	5 years	PO_4-P: 140-525	NH_4-N: <10 - 880	% coverage Cladophora: approx. 0-80%	Article focused on setting target P levels. Highest P levels had highest Cladophora coverage; but a correlation between P & % coverage was not statistically significant. Authors believe P high enough in river at all sites that additional P would have no affect on cladophora growth rates.

Table 4-4 Independent Variables Used in Regression Equations

Variable Quantified	Parameters Used as Independent Variables in Regressions
Nutrient water concentrations	Total phosphorus, phosphate-phosphorus, soluble reactive phosphorus, total nitrogen, total inorganic nitrogen, soluble inorganic nitrogen
Nutrient loading to river or nutrient status of the periphyton	Water conductivity, % cellular nitrogen in periphyton
Periphyton loss through scouring or bed movement	Days between flood events, % time in flood, flood frequency, flow rate, total suspended solids, substrata rock size
Periphyton growth rates	Water temperature

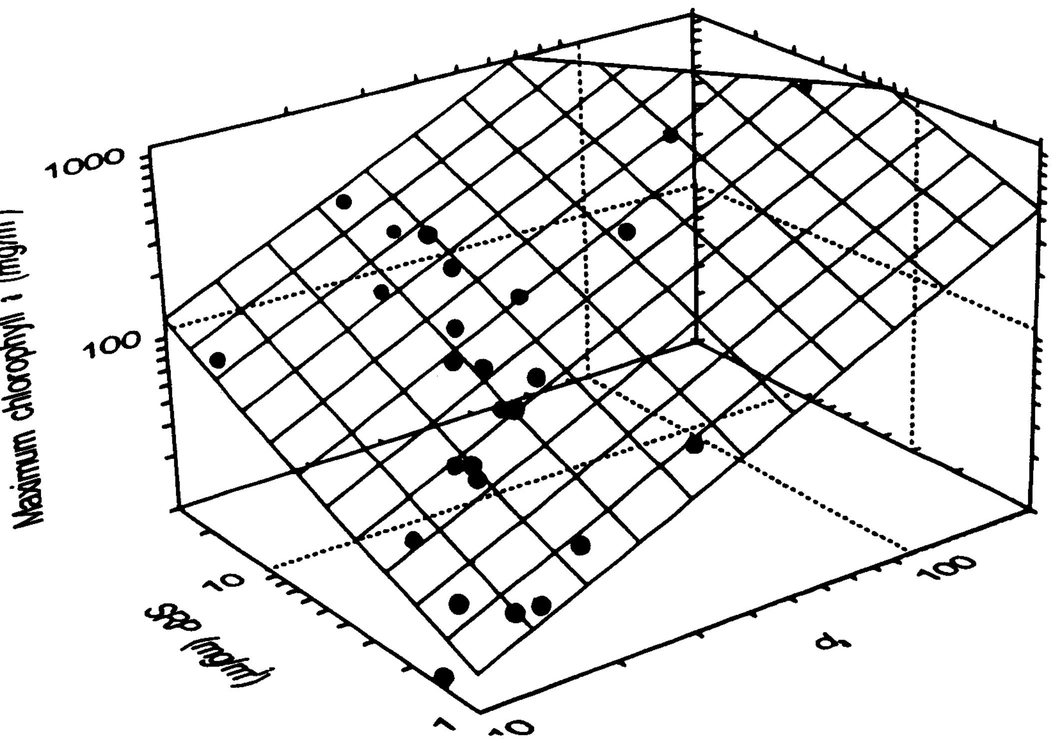
Figure 4-1 Conductivity versus Periphyton Biomass and Total Phosphorus versus Periphyton Biomass for 13 Rivers in Southern Ontario and Quebec, Canada





From Chetelat et al. (1999)
Regression equations derived from the data:
Log(Chl) = 0.002(Cond) + 1.134, (R^2 = 0.71, n=25)
Log(Chl) = 0.905Log(TP) + 0.490, (R^2 = 0.56, n=33)

Figure 4-2 Soluble Reactive Phosphorus (SRP) and Days Between Flood Events (d_a) versus Maximum Periphyton Biomass for 25 Rivers in New Zealand



From Biggs (2000)
Regression equation derived from the data:
Log(max Chl) = 4.716Log(Da) -1.076(Log(Da))2 + 0.494Log(SRP) - 2.714, (R^2 = 0.72, n=30)

5.0 NUTRIENT THRESHOLDS FOR ACCEPTABLE PERIPHYTON BIOMASS

The purpose of this literature review was to identify potentially useful relationships between periphyton biomass and nutrient levels that might be useful in developing potential nutrient criteria in rivers and streams. Before setting nutrient criteria based on such relationships, however, periphyton biomass levels must be more directly linked to impairment of the designated water uses that all water quality criteria are designed to prevent. This section presents information on the nutrient-impairment linkage that should be considered when developing nutrient criteria. Some potential nutrient thresholds associated with impaired conditions were identified from the literature. In addition, the U.S.EPA's water quality criteria recommendations for nutrients for sub-ecoregion 59 (Northeastern Coastal Zone) were compared with other proposed nutrient limits to prevent excessive periphyton biomass. EPA's water quality criteria recommendations for nutrients were substituted into selected regressions and predicted periphyton levels compared with levels considered potentially harmful to designated uses.

5.1 Potential Nuisance Levels of Periphyton Biomass

Once an impairment has been identified, that effect should be linked to a measurable biological parameter which, in turn, should be linked to a nutrient criteria. Many of the papers reviewed in the literature search suggested periphyton levels at which an impairment of water uses might occur. A summary of the periphyton biomass levels identified as potentially impairing is presented in Table 5-1. Excess biomass leads to impairment of aesthetic and recreational use of rivers and streams for most of the limits listed in Table 5-1. From the information presented in Table 5-1, periphyton biomass between 50 to 200 mg/m^2 Chl a or between 20 to 55% of sediment coverage appears to be considered at nuisance levels. However, Nordin (1985) cited impact to aquatic life at periphyton levels exceeding 100 mg/m^2 Chl a and Wharfe (1984) stated that filamentous *Cladophora* sp. coverages greater than 40% could harm fisheries. The information in Table 5-1 is not an exhaustive search of the connection between periphyton levels and damage to river systems. Such a search is outside the scope of this literature review.

5.2 Potential Approaches to Setting Nutrient Criteria

Development of draft nutrient criteria for New England is likely to be based on the results of several approaches using a weight-of-evidence approach (U.S.EPA 2000b, Dodds and Welch 2000). The U.S.EPA Nutrient Criteria Technical Guidance Manual, Rivers and Streams (U.S.EPA 2000b) lists three methods for establishing nutrient criteria in rivers and streams:

- Identification of reference stream reaches based on professional judgement or percentile selections of data plotted as frequency distributions;
- Use of models, and/or examination of system biological attributes to assess the relationships among nutrient and algal variables; and,

- Utilization of published nutrient/algal thresholds.

Two papers by Dodds and his co-workers were identified which utilized one or more of the strategies listed above to develop nutrient criteria. The approaches and results are discussed further below.

Dodds et al. (1997) used regression models and the reference stream approach to establish nutrient criteria for the Clark Fork River in western Montana. Data from 200 sites on rivers and streams in Europe, North American, and New Zealand were analyzed using stepwise multiple linear regression to construct a series of nutrient-linked growth models. The best four regression equations are listed in Table 4-1. Other non-nutrient factors influencing benthic algal biomass such as latitude, temperature, stream gradient, discharge, and light, were also investigated using nonparametric correlation analysis. None of these variable were found to be as useful as a predictor of stream chlorophyll a than TN or TP, however (Dodds et al. 1997).

As indicated earlier, periphyton biomass level in the range of 50-200 mg/m^2 Chl a may result in impairment of water uses. To estimate potentially acceptable nutrient concentrations, periphyton levels of 50, 100, and 200 mg/m^2 Chl a were substituted into the best regression equations. (Dodds et al. 1997) The equations were solved for the nutrient included in the most terms. The value of the other limiting nutrient was calculated assuming that TP varies with TN according to the hypothetical Redfield ratio of 7.23 g N:1 g P (Harris 1986). The results and 95% confidence limits for the predicted nutrient levels are listed in Table 5- 2.

Dodds et al. (1997) also employed the reference reach approach to set nutrient criteria. Six reaches of the Clark Fork River that exhibited subjectively determined acceptable levels of benthic chlorophyll a were sampled and their nutrient levels measured. The mean summer TN and TP concentrations at the reference stations averaged 318 and 20.5 ug/l respectively. This suggests that nutrient levels below these values would result in a cceptable levels of periphyton.

Taking a different approach, Dodds et al. (1998) used a statistical percentile to estimate stream and nutrient parameter values bounding approximate oligotrophic, mesotrophic, and eutrophic river and stream systems. The authors analyzed published data for a large number of distinct temperate stream sites for mean benthic chlorophyll a, maximum benthic chlorophyll a, sestonic chlorophyll a, total nitrogen, and total phosphorus. The boundary between oligotrophic and mesotrophic systems was arbitrarily defined as the lower third of the distribution. Similarly, the boundary between mesotrophic and eutrophic systems was arbitrarily defined as the upper third of the distribution. The results of this analysis are presented in Table 5- 3. Note that most of the periphyton biomass levels described as nuisance levels in Table 5- 1 would be associated with the eutrophic systems as defined by Table 5- 3. It may be expected that trophic states in an ecoregion are unlikely to be equally represented due to differences in geomorphology, climate and watershed land use.

5.3 U.S.EPA Water quality criteria recommendations for nutrients for Rivers and Streams in Level III Ecoregion 59

As part of the development of national nutrient criteria, U.S.EPA has developed draft water quality criteria recommendations for nutrients for aggregate ecoregions. Accordingly, water quality recommendations have been issued for aggregate ecoregion XIV (Eastern Coastal Plains) and for its constituent sub-ecoregions, sub-ecoregion 59 (Northeastern Coastal Zone); sub- ecoregion 63 (Middle Atlantic Coastal Plain); and sub-ecoregion 84 (Atlantic Coastal Pine Barrens) (U.S.EPA 2000a). Sub-ecoregion 59 includes all of Rhode Island , all of Connecticut except the northwest corner, eastern and central Massachusetts, eastern New Hampshire, and the southern tip of Maine . In addition, sub-ecoregion 84 includes representation by some lakes on Cape Cod. Vermont is not included in either sub-ecoregion 59 or 84 and n one of the New England states are included in sub-ecoregion 63. Therefore, only criteria developed for sub-ecoregions 59 and 84 were considered. Further, it should be noted that much of the data available for sub-ecoregion 84 is based on waterbodies located outside of New England, so this database may be less representative of New England but was presented for purposes of comparison.

The EPA water quality recommendations were developed using the reference approach (U.S.EPA 2000a). Reference conditions were based on the 25th percentiles of all nutrient data collected from all reaches. Minimum and maximum values and 25th percentile results for nutrients in sub-ecoregions 59 and 84 are presented in Table 5-4.

To illustrate what potential periphyton biomass values would be expected under reference stream conditions, critical nutrient values (e.g., TP, TN, NO_2 + NO_3) for sub-ecoregions 59 and 84 were substituted into several regression equations including Lohman et al. (1992); Dodds et al. (1997); Chetelat et al. (2999); and Biggs (2000). Except for Chetelat et al.'s regression, all the reported periphyton biomass levels represent mean biomass results. Chetelat et al.'s regression was calculated using site-specific date-specific data instead of site-specific mean data.

Substituting the U.S.EPA water quality criteria recommendations for nutrients into these selected regression equations from Table 4-1 resulted in predicted periphyton biomass ranging from 3 to 74 mg/m^2 Chl a for sub-ecoregion 59 and 3 to 69 mg/m^2 Chl a for sub-ecoregion 84 (Tables 5-5 and 5-6). For sub-ecoregion 59, the results indicate that the recommended criteria would result in periphyton levels likely to be acceptable in most situations. This conclusion was reached because all predicted values were below 100 mg/m^2 Chl a and the average predicted values (for TP -- 41.3, for TN – 59.3 mg/m^2 Chl a) were below or just slightly above 50 mg/m^2 Chl a, the most stringent threshold listed in Table 5-1. Accordingly, it appears that the U.S.EPA water quality nutrient recommendations will not likely result in impairment of designated water uses due to periphyton accumulation.

Table 5-1 Periphyton Biomass Levels Associated with Potential Impairment

Reference	Criteria	Potential Impaired Water Use
Biggs 2000	> 150-200 mg/m^2 Chl a	Aesthetics, recreation, sports fishing
Dodds et al. 1997	> 100 mg/m^2 mean Chl a >150 mg/m^2 max Chl a	na
Nordin 1985	> 50 mg/m^2 Chl a	Recreational usage
Nordin 1985	> 100 mg/m^2 Chl a	Aquatic life
Welch et al. 1988	100-150 mg/m^2 Chl a	Aesthetics, oxygen content and macroinvertebrate diversity unaffected at these levels
Horner et al. 1983	> 100-150 mg/m^2 Chl a > 20% sediment cover	na
Zuur 1992	Seasonal max sediment cover > 40% and/or > 100 mg/m^2 Chl a	Recreational usage
Biggs & Price 1987	≥ 40% sediment cover	Aesthetics
Biggs & Price 1987	≥ 55% sediment cover	Extensive smothering of sediment
Wharfe et al. 1988	Cladophora sediment cover ≥ 40%	Aesthetics, fisheries

Table 5-2 Proposed Nutrient Criteria for the Clark Fork River Based on Regression Equations Between Nutrients and Periphyton Biomass Levels

Target Chl a (mg/m^2)	TN (ug/l)	TP (ug/l)	Lower 95% Chl a (mg/m^2)	Upper 95% Chl a (mg/m^2)
Equations: Function of Log(TN), Log(TN) ^{2}, and Log(TP)				
Mean 50	450	62.3	6.56	170
100	1600	221	26	420
200	3000	415	15.5	436
Max 50	145	20.1	7.8	407
100	275	38.1	29	1380
200	650	90	63	3310
Equations: Function of Log(TP), Log(TP) ^{2}, and Log(TN)				
Mean 50	470	65	9	234
100	1423	197	11	295
200	7570	1020	33	1072
Max 50	115	16	7	352
100	252	35	15	710
200	650	90	28	1356

(from Dodds et al. 1997)

Table 5-3 Suggested Thresholds Between Stream Trophic States Based on Population Distribution

Variable (units)	Oligotrophic-mesotrophic boundary	Mesotrophic-eutrophic boundary	n
Mean benthic chlorophyll (mg/m ^{2})	20	70	286
Maximum benthic chlorophyll (mg/m ^{2})	60	200	176
Sestonic chlorophyll (ug/l)	10	30	292
Total nitrogen (mg/l)	0.70	1.50	1070
Total phosphorus (ug/l)	25	75	1366

(from Dodds et al. 1998)

Table 5-4 U.S.EPA Water Quality Criteria Recommendations for Nutrients for Rivers and Streams in Level III Ecoregions 59 and 84

Parameter	Number of Streams[a]	Reported Values - Min[b]	Reported Values - Max[b]	25th Percentile values[b,c]
Level III Ecoregion 59 - Northeastern Coastal Zone				
TKN (mg/l)	71	0.05	1.45	0.30
NO_2+NO_3 (mg/l)	41	0.10	4.12	0.31
TN (mg/l)	14	0.40	2.13	0.57
TP (ug/l)	87	2.50	907.50	23.75
Turbidity (NTU)	23	0.84	2.58	1.68
Turbidity (FTU)	33	0.75	6.13	1.26
Turbidity (JCU)	---	---	---	---
Chlorophyll a (ug/L) - S[d]	---	---	---	---
Level III Ecoregion 84 - Atlantic Coastal Pine Barrens				
TKN (mg/l)	62	0.05	2.26	0.24
NO_2+NO_3 (mg/l)	61	0.01	5.09	0.24
TN (mg/l)	11	0.24	2.18	0.48
TP (ug/l)	65	2.5	276.25	6.88
Turbidity (NTU)	---	---	---	---
Turbidity (FTU)	19	0.75	31.2	1.78
Turbidity (JCU)	2	3.0	5.01	3.0
Chlorophyll a (ug/L) - S	3	3.09	16.58	3.09[e]

(from U.S.EPA 2000a)

(a) The number of streams and rivers for which data existed for the summer months.

(b) All values (min, max, and 25 th percentiles) are based on waterbody medians. All data for a particular parameter within a stream for the decade were reduced to one median for that stream.

(c) Calculated by taking the median of the four seasonal 25 th percentiles. If a season is missing, the median was calculated with three seasons of data.

(d) Chlorophyll a measured by Spectrophotometric method with acid correction.

(e) Calculated median from less than three seasons' data.

Table 5-5 Estimated Periphyton Biomass at U.S.EPA Water Quality Criteria Recommendations for Nutrients for Level III Ecoregion 59

Reference	Recommended Criteria for Total Phosphorus (ug/L)	Periphyton Biomass (mg/m^2 Chl a)	Notes
Lohman et al. 1992	23.75	52	Mean biomass
Chetelat et al. 1999		54	
Dodds et al. 1997		23	Mean biomass, TN calculated from TP using Redfield Ratio
Dodds et al. 1997		36	Mean biomass, U.S.EPA criteria used for TN
Reference	**Recommended Criteria for TN (mg/L)**	**Periphyton Biomass**	**Notes**
Lohman et al. 1992	0.57	74	Mean biomass
Chetelat et al. 1999		60	
Dodds et al. 1997		59	Mean biomass, TP calculated with Redfield Ratio
Dodds et al. 1997		44	Mean biomass, Used U.S.EPA criteria for TP
Reference	**Recommended Criteria for NO_3+NO_2 (mg/L)**	**Mean Periphyton Biomass**	**Notes**
Biggs 2000	0.31	3	7 days between floods
		21	30 days between floods
		49	60 days between floods

Table 5-6 Estimated Periphyton Biomass at U.S.EPA Water Quality Criteria Recommendations for Nutrients for Level III Ecoregion 84

Reference	Recommended Criteria for Total Phosphorus (ug/L)	Periphyton Biomass (mg/m^2 Chl a)	Notes
Lohman et al. 1992	6.88	30	Mean biomass
Chetelat et al. 1999		18	
Dodds et al. 1997		7	Mean biomass, TN calculated from TP using Redfield Ratio
Dodds et al. 1997		17	Mean biomass, EPA criteria used for TN
Reference	**Recommended Criteria for TN (mg/L)**	**Periphyton Biomass**	**Notes**
Lohman et al. 1992	0.48	69	Mean biomass
Chetelat et al. 1999		51	
Dodds et al. 1997		52	Mean biomass, TP calculated with Redfield Ratio
Dodds et al. 1997		29	Mean biomass, Used EPA criteria for TP
Reference	**Recommended Criteria for NO_3+NO_2 (mg/L)**	**Mean Periphyton Biomass**	**Notes**
Biggs 2000	0.24	3	7 days between floods
		19	30 days between floods
		46	60 days between floods

6.0 APPLICATION TO DEVELOPMENT OF NUTRIENT CRITERIA

The application of the results of the nutrient-periphyton review was evaluated with regard to its implications for the development of ecoregional nutrient criteria for rivers and streams in New England. In other words, the potential for potential periphyton-based impairment of designated water uses to be applied as part of the overall development of nutrient criteria for rivers and streams was assessed. A preliminary evaluation indicates that there is often a strong linkage between nutrients and periphy ton levels and indirectly to potential impairment of water uses. However, this nutrient-designated use impairment linkage needs to be considered in a relatively defined context of applicability to selected streams and small rivers, as there are many waterbodies for which non-nutrient factors and/or lack of a periphyton community will invalidate such a relationship. Nevertheless, it appears that consideration of periphyton is a likely important component in developing nutrient criteria for rivers and streams.

The main conclusions of this review of the nutrient-periphyton literature are:

- Nutrient control of periphyton biomass is expressed only in the absence of many other non-nutrient limiting factors such as shading, grazing, scour, etc. Therefore, the applicability of nutrient criteria to streams and rivers may be limited both spatially and temporally;

- Potentially useful predictive relationships between nutrients and periphyton biomass exist and may be the basis for estimating the effect of different levels of nutrients ;

- Impairment of designated uses (aesthetics, aquatic life support, recreation, etc.) by periphyton has been noted by professional judgment at high biomass concentrations, usually in excess of 100 mg/m^2 Chl a; and

- Estimation of periphyton biomass under current U.S.EPA water quality nutrient recommendation values suggests that those nutrient levels would not result in ready impairment of the waterbodies.

As the results of the literature review indicate, and in agreement with the Nutrient Criteria Technical Guidance Manual, Rivers and Streams (U.S.EPA 2000b), it is important to derive protective nutrient values in the absence of non-nutrient factors that would potentially limit or influence growth. Thus, for periphyton-dominated streams for which this criteria is most relevant, the goal is to derive nutrient levels associated with acceptable periphyton biomass for streams with good light availability, sufficient micro-nutrients (e.g., silica, iron, molybdenum, copper, etc), adequate and stable substrate and in the absence of heavy grazing pressure, scouring flows and temperature extremes. Accordingly, the applicability of these criteria will vary seasonally and will be most relevant during late spring-summer periods of high solar illumination in non-turbid, uncanopied streams during moderate-to-low flow periods.

However, this seasonal strength of association between nutrients and ecological response is not unlike that seen in lakes and ponds, where nutrient effects are often most apparent in the epilimnion (e.g., high phytoplankton biomass, low transparency) during late summer. Therefore, using a summer index period of periphyton biomass as the basis for deriving acceptable nutrient levels in streams is consistent with this approach. As with lakes and ponds, if protective nutrient criteria are established for the critical summer index period, such levels would be conservative limits for the periods of the year when nutrient-limited growth is less likely.

The predictive relationships discussed in Section 4.0 provide good evidence that it should be possible to use a range of regressions to estimate algal biomass at ambient nutrient levels. Several regressions should be used, given the potential differences in stream systems, periphyton assemblages, and seasonal effect s that exist between all the studies. But Section 4.0 also indicates that it is very important to make sure that non-nutrient factors are taken into account or the predictive regressions will fail to be useful. Alternatively, one approach for developing criteria may be simply to assume the existence of nutrient-limited conditions throughout the watershed for streams of a certain order. This would be highly conservative for some streams (e.g., heavily shaded, poor bottom substrate) but could be used for a default initial value in lieu of more site-specific information.

The impact of periphyton o n designated water uses is poorly understood by comparison with the effect of phytoplankton levels on aesthetics, turbidity, frequency of nuisance blooms, dissolved oxygen fluctuations, etc. This is probably due to a variety of factors including: the patchy distribution and difficulty of assaying periphyton levels; fluctuations in the nutrient levels in streams, the influence of stream velocity in reducing or scouring algal biomass , and a poor lack of understanding of the causal effects. Regardless, there seems to be good professional agreement regarding unacceptable levels of periphyton although the scientific rationale for deriving such judgments is usually not provided. A periphyton biomass of 150-200 mg/m^2 Chl a is considered unacceptable by a variety of authors for a variety of different streams. These levels may be based more on an aesthetic threshold rather than on an exceedance based on specific stream receptors. However, the use of biocriteria (i.e., non-chemical measures of stream water quality) should be useful in providing a more defensible means of distinguishing levels of impact. On the other ha nd, defining the lower end of acceptable biomass where no impact occurs will likely be more difficult. Looking at the available thresholds listed in Table 5-1, it is suggested that a consensus value of 100 mg/m^2 Chl a would be reasonable.

As noted earlier, the Nutrient Criteria Technical Guidance Manual, Rivers and Streams (U.S.EPA 2000b) identified three methods for establishing nutrient criteria in rivers and streams (other methods may be available):

- use of reference stream reaches (based on best professional judgment) and/or percentile selections of reference and general stream data;

- applying predictive relationships to select nutrient concentrations that will resu lt in appropriate levels of algal biomass; and,

- developing criteria from thresholds established in the scientific literature .

In this review we have touched upon all three methods of criteria development and/or used more than one in combination. Using the predictive equations and the 25^{th} percentile values available from the sub-ecoregion water quality recommendations for TP of 23.8 ug/L, it was estimated that between 23-54 mg/m^2 Chl a would be produced. Using the 25^{th} percentile value for TP of 0.57 mg/L, the corresponding biomass estimates would be 44 to 74 mg $/m^2$ Chl a. As noted earlier, the range of these predicted responses are well below the consensus threshold value.

In reviewing the different approaches to nutrient criteria, the suggested approach of creating surrogate oligotrophic, mesotrophic, and eutrophic waterbody designations by dividing up the frequency distribution by the lower and upper thirds (i.e., the 33^{rd} and 66^{th} percentiles) does not seem significantly different than any other assignment of percentiles. Moreover, the use of the trophic terms implies a perhaps inappropriate set of limnological analogies that may have little utility in stream classification. Certainly, there is no evidence to suggest the rivers and streams in New England are neatly and evenly divided among the trophic classification; in fact, there is probably good evidence to show that they are not since so many other factors may control biomass independent of nutrients. Use of this analogy approach probably creates more confusion tha n aids the development of nutrient criteria.

An additional factor that also needs to be considered in nutrient criteria development is the potential impact of nutrients on downstream receiving waters. None of the papers we reviewed included this downstream impact analysis since it was outside the scope of the individual studies. However, States and Tribes will have to consider sensitive downst ream waterbodies when establishing nutrient criteria for a river or stream, which may lead to more stringent values than if only the immediate in -stream impairment is considered.

7.0 REFERENCES

Aizaki, M. and K. Sakamoto. 1988. Relationships between water quality and periphyton biomass in several streams in Japan. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angerwandte Limnologie 23:1511-1518.

Biggs, B.J.F. 1988. Algal proliferations in New Zealand's shallow stony foothills-fed rivers: Toward a predictive model. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angerwandte Limnologie 23:1405-1411.

Biggs, B.J.F. 1995. The contribution of disturbance, catchment geology and land use to the habitat template of periphyton in stream ecosystems. Freshwater Biology 33:419-438.

Biggs, B.J.F. 1996. Patterns in Benthic Algae of Streams. in "Algal Ecology, Freshwater Benthic Ecosystems" R.J. Stevenson, M.L. Bothwell, and R.L. Lower (eds.). Academic Press, New York.

Biggs, B.J.F. 2000. Eutrophication of streams and rivers: dissolved nutrient-chlorophyll relationships for benthic algae. Journal of the North American Benthological Society 19:17-31.

Biggs, B.J.F. and M.E. Close. 1989. Periphyton biomass dynamics in gravel bed rivers: the relative effects of flows and nutrients. Freshwater Biology 22:209-231.

Biggs, B.J.F. and G.M. Price. 1987. A survey of filamentous algal proliferations in New Zealand rivers. N.S.J. Mar. Freshwater Res. 21:175-191.

Biggs, B.J.F and H.A. Thomsen. 1995. Disturbance in stream periphyton by perturbation in shear stress: time to structural failure and differences in community resistance. Journal of Phycology 30:807-818.

Biggs, B.J.F., R.J. Stevenson, and R.L. Lowe. 1998a. A habitat matrix conceptual model for stream periphyton. Archiv. fur Hydrobiologie. 143:25-56.

Biggs, B.J.F., C. Kilroy and R.L. Lowe. 1998b. Periphyton development in three valley segments of a New Zealand grassland river : test of a habitat matrix conceptual model within a catchment. Arch. Hydrobiol. 143:147-177.

Biggs, B.J.F., A. Smith and M.J. Duncan. 1999. Velocity and sediment disturbance of periphyton in headwater streams: biomass and metabolism. Journal of the North American Benthological Society 18:222-241.

Borchardt, M.A. 1996. Nutrients in "Algal Ecology, Freshwater Benthic Ecosystems" R.J. Stevenson, M.L. Bothwell, and R.L. Lower (eds.). Academic Press, New York.

Bothwell, M.L. 1989. Phosphorus - limited growth dynamics of lotic periphytic diatom communities: areal biomass and cellular growth rate responses. Canadian Journal of Fisheries and Aquatic Sciences 46:1293-1301.

Bourassa, N. and A. Cattaneo. 1998. Control of periphyton biomass in Laurentian streams (Quebec). Journal of the North American Benthological Society 17:420-429.

Burton, T.M., M.P. Oemke, and J.M. Molloy. 1991. Contrasting effects of nitrogen and phosphorus additions on epilithic algae in a hardwater and a softwater stream in Northern Michigan. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angerwandte Limnologie 24:1644-1653.

Carrick, J.H., R.L. Lowe, and J.T. Rotenberry. 1988. Guilds of benthic algae along nutrient gradients: relationships to algal community diversity. Journal of the North American Benthological Society 7:117-128.

Chessman, B.C., P.E. Hutton, and J.M. Burch. 1992. Limiting nutrients for periphyton growth in sub-alpine, forest, agricultural, and urban streams. Freshwater Biology 28:349-361.

Chetelat, J., F.R. Pick, and A. Morin. 1999. Periphyton biomass and community composition in rivers of different nutrient status. Canadian Journal of Fisheries and Aquatic Sciences 56:560-569.

Dodds, W.K. and E.B. Welch. 2000. Establishing nutrient criteria in streams. Journal of the North American Benthological Society 19:186-196.

Dodds, W.K., V.H. Smith, and B. Zander. 1997. Developing nutrient targets to control benthic chlorophyll levels in streams: a case study of the Clark Fork River. Water Research 31:1738-1750.

Dodds, W.K., J.R. Jones, and E.B. Welch. 1998. Suggested classification of stream tropic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. Water Research 32:1455-1462.

Francoeur, S.N., B.J.F. Biggs, R.A. Smith, and R.L. Lowe. 1999. Nutrient limitation of algal biomass accrual in streams: seasonal patterns and a comparison of methods. Journal of the North American Benthological Society 18:242-260.

Harris, G.P. 1986. Phytoplankton ecology: structure, function and fluctuation. Chapman and Hall, Cambridge, UK.

Hill, W.R., H.L. Boston, and A.D. Steinman. 1992. Grazers and nutrients simultaneously limit lotic primary productivity. Canadian Journal of Fisheries and Aquatic Sciences 49:504-511.

Horner, R.R., and E.B. Welch. 1981. Stream Periphyton Development in relation to current velocity and nutrients. Canadian Journal of Fisheries and Aquatic Sciences 38:449-457.

Horner, R.R., E.B. Welch, and R.B. Veenstra. 1983. "Development of nuisance periphytic algae in laboratory streams and rivers in relation to enrichment and velocity". In "Periphyton of Freshwater Ecosystems" R.G. Wetzel, (ed.). Dr. W. Junk Publishers, The Hague.

Horner, R.R, E.B. Welch, M.R. Seeley, and J.M. Jacoby. 1990. Responses of periphyton to changes in current velocity, suspended sediment and phosphorus concentration. Freshwater Biology 24:215-232.

Humphrey, K.P. and R.J. Stevenson. 1992. Responses of benthic algae to pulses in current and nutrients during simulations of subscouring spates. Journal of the North American Benthological Society 11:37-48.

Jones, J.R., M.M. Smart, and J.N. Burroughs. 1984. Factors related to algal biomass in Missouri Ozark streams. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angerwandte Limnologie 22:1867-1875.

Lamberti, G.A. and A.D. Steinman. 1997. A comparison of primary production in stream ecosystems. Journal of the North American Benthological Society 16:95-104.

Leland, H.V. 1995. Distribution of phytobenthos in the Yakima River basin, Washington, in relation to geology, land use, and other environmental factors. Canadian Journal of Fisheries and Aquatic Sciences 52:1108-1129.

Lohman, K., J.R. Jones, and B.D. Perkins. 1992. Effects of nutrient enrichment and flood frequency on periphyton biomass in northern Ozark streams. Canadian Journal of Fisheries and Aquatic Sciences 49:1198-1205.

Lowe, R.L, S.W. Golladay, and J.R. Webster. 1986. Periphyton response to nutrient manipulation in streams draining clearcut and forested watersheds. Journal of the North American Benthological Society 5:221-229.

McCormick, P.V. 1994. Algae as indicators of environmental change. Journal of Applied Phycology 6: 509-526.

Miltner, R.J. and E.T. Rankin. 1998. Primary nutrients and the biotic integrity of rivers and streams. Freshwater Biology 40:145-158.

Mulholland, P.J., E.R. Marzolf, S.P. Hendricks, and R.V. Wilkerson. 1995. Longitudinal patterns of nutrient cycling and periphyton characteristics in streams, a test of upstream-downstream linkage. Journal of the North American Benthological Society 14:357-370.

Munn, M.D., L.L. Osborne, and M.J. Wiley. 1989. Factors influencing periphyton growth in agricultural streams of Central Illinois. Hydrobiologia 174:89-179.

Nordin, R.N. 1985. "Water Quality Criteria for Nutrients and Algae (Technical Appendix)." Water Quality Unit, Resource Quality Section, Water Management Branch, British Columbia Ministry for the Environment, Victoria.

Perrin, C.J., M.L. Bothwell, and P.A. Slaney. 1987. Experimental enrichment of a coastal stream in British Columbia: effects of organic and inorganic additions on autotrophic periphyton production. Canadian Journal of Fisheries and Aquatic Sciences 44:1247-1256.

Rast, W., V.H. Smith, and J.A. Thornton. 1989. Characteristics of eutrophication. Pages 37-63 in S. Ryding and W. Rast (eds). The control of eutrophication in lakes and reservoirs. UNESCO and Parthenon, Paris.

Rosemond, A.D. 1993. Interactions among irradiance, nutrients, and herbivores constrain a stream algal community. Oecologia 94:585-594.

Rosemond, A.D. 1994. Multiple factors limit seasonal variation in periphyton in a forest stream Journal of the North American Benthological Society 13:333-344.

Russo, R.C. 1985. Ammonia, nitrite and nitrate. Pages 455-471 in G.M. Rand and S.R. Petrocelli (eds.). Fundamentals of aquatic toxicology. McGraw-Hill, Washington, DC.

Schanz, F. and H. Juon. 1983. Two different methods of evaluating nutrient limitations of periphyton bioassays, using water from the River Rhine and eight of its tributaries. Hydrobiologia 102:187-195.

Sumner, W.T. and S.G. Fisher. 1979. Periphyton production in Fort River, Massachusetts. Freshwater Biology 9:205-212. U.S.DA. 1999. A Procedure to Estimate the Response of Aquatic Systems to Changes in Phosphorus and Nitrogen Inputs. National Water and Climate Center. National Resource Conservation Service. October.

U.S.EPA. 1998. National Strategy for the Development of Regional Nutrient Criteria. Office of Water. EPA 822-R-98-002. June.

U.S.EPA. 2000a. Nutrient Criteria, Technical Guidance Manual, Rivers and Streams. Office of Water. ~~Office of Science and Technology. EPA-822-B-00-002. July.~~

U.S.PA. 2000b. Ambient Water Quality Criteria Recommendations. Information Supporting the Development of State and Tribal Nutrient Criteria. Rivers and Streams in Nutrient Ecoregion XIV. Office of Water. EPA-822-B-00-022. December.

Van Niewenhuyse, E.E. and J.R. Jones. 1996. Phosphorus-chlorophyll relationship in temperate streams and its variation with stream catchment area. Canadian Journal of Fisheries and Aquatic Sciences 53:99-105.

Vannote, R.L, G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Walton, S.P., E.B. Welch, and R.R. Horner. 1995. Stream periphyton response to grazing and changes in phosphorus concentration. Hydrobiologia 302:31-46.

Welch, E.B., J.M. Quinn and C.W Hickey. 1992. Periphyton biomass related to point-source nutrient enrichment in seven New Zealand streams. Water Research 26:669-675.

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

Welch, E.B., R.R. Horner, and C.R. Patmont. 1989. Prediction of nuisance periphytic biomass: A management approach. Water Research 23:401-405.

Wharfe, J.R,, K.S. Taylor, and H.A.C. Montgomery. 1984. The growth of cladophora glomerata in a river receiving sewage effluent. Water Research 18:971-979.

Wold, A.P. and A.E. Hershy. 1999. Spatial temporal variability of nutrient limitation in 6 north shore tributaries to Lake Superior. Journal of the North American Benthological Society 18:2-14.

Yang, J-R, B.K. Basu, P.B. Hamilton and F. R. Pick. 1997. The development of a true riverine phytoplankton assemblage along a lake-fed lowland river. Arch. Hydrobiol. 140:243-260.

Zuur, B. ed. 1992. Water Quality Guidelines No. 1: Guidelines for the Control of Undesirable Biological Growths in Water." New Zealand Ministry for the Environment, Wellington.

APPENDIX A – ABSTRACTS