New Zealand Periphyton Guideline:

Detecting, Monitoring and Managing Enrichment of Streams

Prepared for
Ministry for the Environment

by Barry J F Biggs,
NIWA, Christchurch, June 2000

Foreword

New Zealand is a nation of water lovers. Nearly all of us have memories of tramping, fishing, swimming, picnics or holidays at rivers. Much of our adventure tourism industry also revolves around rivers. However, our modern lifestyle is placing increased pressure and stress on our rivers. Nutrients entering rivers and changes in flows can contribute to periphyton proliferation.

Periphyton is the slime and algae found on the beds of streams and rivers. It is essential for the function of healthy ecosystems, but when it proliferates it can become a nuisance, degrading swimming and fishing spots, clogging irrigation and water supply intakes.

When the Ministry published the first water quality guideline, *Water Quality Guidelines No1: guidelines for the control of undesirable growths in water* in 1992, it represented state-of-the-art information on managing nuisance biological growths in rivers and streams. However since then, not only has there been significant new research on the factors controlling periphyton, but there has been a significant shift in water management and periphyton is no longer managed as a problem but is also recognised as a key component of aquatic ecosystems.

This guideline has been developed collaboratively, with people from a range of agencies, including regional councils, Department of Conservation and Fish and Game New Zealand, providing valuable input. Our thanks go to all of the people who have made a contribution to the guideline. As a result of the collaborative, this guideline not only updates part of that first water quality guideline published in 1992, but also significantly expands the information covered. This is particularly important because it shows just how far we have come in water management in the nine years since the Resource Management Act 1991 was introduced.

We (Barry Biggs and the periphyton working group) have designed this guideline to help water managers determine the likely impacts of land and water developments on stream periphyton communities. It also provides tools to help them better manage the competing demands being placed on rivers.

This guideline needs to be used in the broader context of resource management and follow the approach first developed in the *Flow Guidelines for Instream Values* published in 1998. To this end, these guidelines are not a prescriptive recipe. They provide the information necessary for water managers to set objectives, evaluate and/or predict the natural condition of rivers and determine the appropriate management responses for individual situations.

I know that you will find these guidelines useful and that they will help you in the challenging task of water management in the 21st century.

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While drawing on information from the international literature, the core of this manual is based on extensive research carried out in New Zealand and funded through the Public Good Science Fund (most recently through the NIWA programmes "Environmental Hydrology and Habitat Hydraulics" and "River Ecosystems – Land Use Interactions") and also the Department of Conservation. This funding has been greatly appreciated and enabled me (and several of my colleagues) to start to unravel and understand some of the complexity of factors controlling periphyton development in streams and rivers of New Zealand. Through these *Guidelines*, I am hopeful that this knowledge will now be more widely available and benefit water management, the public, and stream ecosystems generally. The preparation of the *Guidelines* was funded by the Ministry for the Environment.

Executive summary

Periphyton is the slime and algae found on the bed of streams and rivers. This group of organisms is essential for ecosystem functioning but under certain circumstances can proliferate, causing water resources management problems such as degrading aesthetic, recreational and biodiversity values. Proliferations can also taint water, be toxic to animals, and clog abstraction intakes. New Zealand streams are particularly prone to such proliferations because of the gravel/cobble nature of the beds, high-intensity sunlight, warm waters and enrichment from natural and anthropogenic causes (eg, nutrient-rich rocks, agricultural land use). Thus, periphyton communities should be considered as a possible issue in any planning or resource assessments involving streams and rivers. Indeed, under the Resource Management Act 1991 (RMA), regional councils have the responsibility for ensuring that the life-supporting capacity of the environment is maintained but that nuisance growths of organisms are not enhanced. These *Guidelines* are designed to help water managers determine the likely impacts of land and water developments on stream periphyton and thus assist to facilitate the intent of the RMA.

This *Guideline* gives a background review of the structure and value of periphyton communities in streams, factors controlling growth and composition of periphyton, and the effects of human activities on the community. A set of guidelines is then developed to help prevent degradation of aesthetic/recreational, biodiversity and angling values by excessive enrichment of streams (and resultant proliferations of periphyton). The biomass and cover guidelines are summarised below.

Provisional biomass and cover guidelines for periphyton growing in gravel/cobble bed streams for three main instream values (AFDM = ash-free dry mass).

Instream value/variable	Diatoms/cyanobacteria	Filamentous algae
Aesthetics/recreation (1 November – 30 April)		
Maximum cover of visible stream bed	60 % >0.3 cm thick	30 % >2 cm long
Maximum AFDM (g/m^2)	N/A	35
Maximum chlorophyll *a* (mg/m^2)	N/A	120
Benthic biodiversity		
Mean monthly chlorophyll *a* (mg/m^2)	15	15
Maximum chlorophyll *a* (mg/m^2)	50	50
Trout habitat and angling		
Maximum cover of whole stream bed	N/A	30 % >2 cm long
Maximum AFDM (g/m^2)	35	35
Maximum chlorophyll *a* (mg/m^2)	200	120

The percentage cover values apply to the part of the bed that can be seen from the bank during summer low flows (usually <0.75 m deep) or walked on. The biomass guidelines are expressed in terms of biomass per unit of exposed substrata (ie, tops and sides of stones) averaged across the full width of the stream or river in a reach. A reach is defined as a relatively homogeneous section of stream channel. Most commonly this will be a run, but this should be clearly specified in setting consent conditions. For maintenance of benthic biodiversity (ie, a “clean-water” benthic fauna), the guidelines are given in terms of mean monthly and maximum chlorophyll *a*. The aesthetics/recreation guidelines are only expected to be applied over the summer months (1 November – 30 April).

Relationships are also developed between peak biomass of periphyton and the primary controlling variables of time available for growth (ie, time between flood events) and nutrient concentrations in the water (as mean monthly concentrations measured over at least a year). These relationships are then used to develop nutrient guidelines for various growth periods to ensure that peak biomass doesn’t exceed the biomass guidelines for the various instream values as summarised below.

Soluble inorganic nitrogen (SIN = $NO_3 - N + NO_2 - N + NH_4 - N$) and soluble reactive phosphorus (SRP) concentrations (mg/m^3) predicted to prevent maximum biomass from exceeding the given levels. The nutrient concentrations are to be determined as mean monthly concentrations over a year. Limits of detection are assumed to be around 5 mg/m^3 for SIN and 1 mg/m^3 for SRP if analyses are carried out using standard autoanalyser techniques. The chlorophyll a at 120 mg/m^2 refers to filamentous green algae dominated communities whereas the chlorophyll a at 200 mg/m^2 refers to diatom dominated communities. AFDM = ash-free dry weight.

Study	Chlorophyll *a* = 50		AFDM=35 Chlorophyll *a* = 120 Chlorophyll *a* = 200	
Days of accrual	SIN	SRP	SIN	SRP
20	<20	<1	<295	<26
30	<10	<1	<75	<6
40	<10	<1	<34	<2.8
50	<10	<1	<19	<1.7
75	<10	<1	<10	<1
100	<10	<1	<10	<1

In using the soluble inorganic nutrient guidelines for developing consent conditions, it is important to recognise that the specific nutrient limiting periphyton growth needs to be identified and consent conditions set in terms of that single nutrient. It is usually unnecessary to specify conditions in terms of both nitrogen and phosphorus. One of these nutrients will generally be in surplus and therefore at much higher concentrations than the guideline shown in the above table. Also, it is important that the background soluble nutrient concentrations coming into the reach of interest are evaluated thoroughly. This will usually involve monthly sampling for a year to characterise temporal dynamics and get an estimate of the mean concentrations. This will provide the basis for nutrient supply calculations associated with any discharges in relation to the instream management objective and associated guideline biomass.

A number of mitigation options are discussed in the event that nutrient control to reduce the potential for proliferations is not feasible. These include riparian shading, artificial flushing events in regulated rivers, and optimising benthic invertebrate habitat to increase losses through grazing activity.

The technical manual details methods for surveying and sampling periphyton, analysis of biomass (ash-free dry mass and chlorophyll *a*), and analysis of the taxonomic composition of the communities.

The present *Guidelines* do not cover proliferations caused by sewage fungus. The 1992 Ministry for the Environment *Water Quality Guidelines* #1 are still current for those communities.

1 Background and structure to *Guidelines*

1.1 Background

Periphyton is found in all aquatic habitats but is often most conspicuous in streams and rivers. Periphyton is the slime coating stones, wood, weeds or any other stable surfaces in streams. The community may sometimes be difficult to detect, but gives these surfaces a brown or brown-green colouring. Scrape a stone in a stream and the pile of brown material that accumulates will be periphyton. In some situations it can proliferate and form clouds or mats of green or brown filaments over the stones or in pools. This is when periphyton is at its most conspicuous (Figure 1).

Figure 1: The filamentous alga *Vaucheria* forming a rich green mat of periphyton over sands in a spring-fed stream near Pupu Springs, Takaka.

The periphyton community is fundamental for sustaining life, affecting natural character and determining the intrinsic values of stream ecosystems. Indeed, this community contains the main primary producers of streams, the transducers of light energy and mineral nutrients into food for most other forms of stream life. Thus, the effects should always be evaluated on the form, quantity and functioning of periphyton communities of any developments involving the use of water from streams or changes in stream channel structure.

In 1992, the Ministry for the Environment published the document *Water Quality Guidelines No. 1: Guidelines for the control of undesirable growths in water* (MfE, 1992) . When published, those *Guidelines* represented the state of the art in matters concerning controlling nuisance biological growths in streams and rivers. The *1992 Guidelines* covered sewage fungus, phytoplankton, periphyton and macrophytes. However, since then there has been significant new research on periphyton and the factors controlling its growth. These new *Guidelines* therefore focus just on periphyton, taking advantage of much of this new research to develop an updated set of tools and understandings that will improve our ability to manage periphyton growth in streams.

1.2 Purpose

The purpose of this guideline is to provide an objective way of managing periphyton in streams, both for its important primary production role in ecosystems and for managing nuisance proliferations. These *Guidelines* do not provide any direction on resolving competition between instream values such as trout habitat and out-of-stream uses such as abstraction. This competition must be resolved on a case by case basis, using the following to guide the decision – Parts II, III, IX and Schedule III of the Resource Management Act 1991(RMA), regional policy statements, regional plans and consultation with communities of interest.

These Guidelines are not a prescriptive recipe. They provide the information necessary for users to set objectives, evaluate and/or predict the natural conditions and determine appropriate management responses for individual situations.

1.3 Management approach suggested in these *Guidelines*

Effective management requires clear and measurable goals so that progress can be assessed. You must know what you are managing your waterway for. The recommended approach for managing periphyton used in these *Guidelines*, as shown in Figure 2, provides a framework for identifying values, setting objectives and monitoring the effects of management responses. It is the same approach used in the *Flow Guidelines for Instream Values* (MfE, 1998). The process as it relates to periphyton is as follows:

1. Identify instream and out-of-stream values for the water resource concerned (eg, irrigation, contact recreation, particular fish or bird habitat).
2. Use a classification of physical features to determine whether values are compatible with the natural physical constraints of the system. For example, if the local geology is dominated[1] by nutrient-rich Tertiary marine siltstones, filamentous algal blooms are likely to occur naturally.

Note: The 1992 Guidelines remain current for sewage fungus and the impact of organic contamination. Those issues are not covered in these revised periphyton Guidelines.

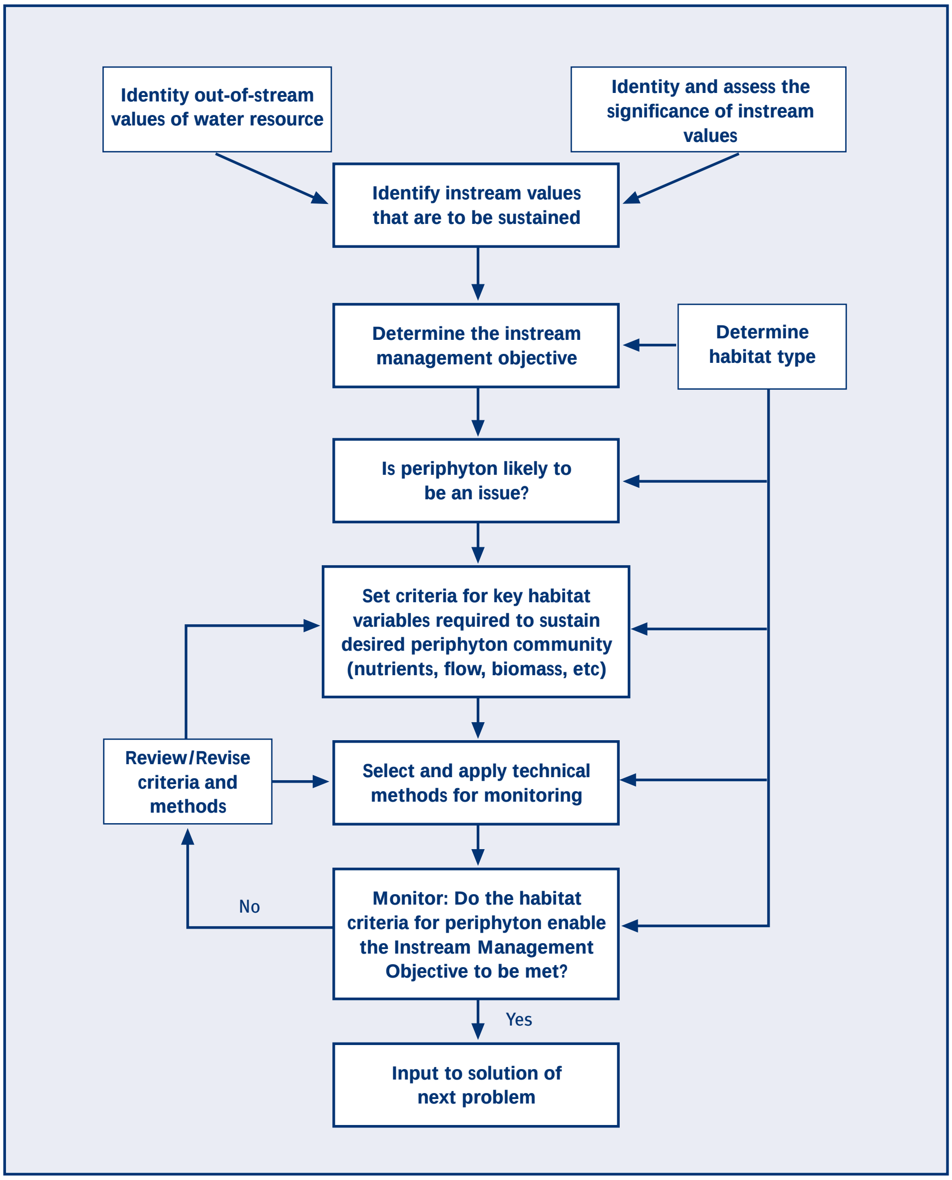
[1] *The use of the word "dominated" in this context does not imply that a characteristic is present in proportions greater than 50 percent. Rather, "dominant" means that a characteristic is present in proportions large enough to be the predominant controller of instream responses.*

3. Determine instream management objectives (ISMOs) for identified values, such as:
    A. Maintain instream conditions which allow Grade 3 whitewater rafting over the summer rafting season (1 November – 30 April).
    B. Maintain instream conditions which allow passage of salmon during the period 1 January – 1 May.
    C. Maintain instream conditions of <30 percent cover of filamentous algae in order to allow swimming over the summer (1 November – 30 March).
    D. Allow no degradation of benthic invertebrate communities currently comprised of >50 percent Ephemeroptera + Plecoptera + Tricoptera taxa.
    E. Maintain trout habitat at a level which will allow at least 0.3 fish per square metre in the following rivers etc.

    To be most effective, ISMOs should be defined in terms of space and time and specify a level of protection. In the above examples, defining where an ISMO applies could be by way of including a description of the area in the ISMO itself, or it could be linked to regional classification maps etc. The level of protection is signified by specific measurable degrees such as "… allow Grade 3 whitewater rafting …" or "… benthic invertebrate communities currently comprised of >50 percent Ephemeroptera …".

    Levels of protection are important qualifiers for ISMOs. They give added flexibility in the way systems are managed with the result that a greater range of values and end-uses can potentially be catered for. Using levels of protection also results in clearly measurable objectives. Levels of protection do, however, highlight the need for good, defensible, relationships or models to enable accurate predictions to be made of the effects of more subtle changes in water management regimes (and thus controlling parameters) on periphyton biomass and community composition.
4. Decide whether periphyton is likely to be an issue for any identified values or ISMOs (given the habitat type of the stream or river). Using the above example, periphyton has the potential to be a nuisance in ISMO C whereas for ISMOs D and E, periphyton will be important for ecosystem maintenance. Periphyton is unlikely to be of major concern for ISMOs A and B.
5. Using ISMOs and habitat type information select appropriate parameters, methods and sites for monitoring. For example, for ISMO C, the parameter would be periphyton biomass. The sample-collection method is habitat-dependent, such as scraping the community from a set area for gravel/cobble-bed streams.
6. If monitoring results indicate that suitable boundaries or levels are being exceeded, appropriate management action needs to be taken – for example, reviewing resource consent conditions.

Figure 2: General procedures for planning, setting consent criteria and verifying appropriateness of consent criteria for managing instream values in relation to periphyton (based on Figure 9 of the *Flow Guidelines for Instream Values* (MfE, 1998)).



1.4 Structure of *Guidelines*

For reasons of size and ease of use, these *Guidelines* are separated into two volumes. This document deals with general concepts, factors controlling periphyton growth in streams, how human activities can affect periphyton, communities found in New Zealand streams, using periphyton to evaluate or monitor water quality and guidelines for biomass and nutrient supply to avoid compromising instream values. **The technical manual** deals with the technical issues of how to measure and evaluate periphyton. It includes descriptions of methods as well as a section to enable the identification of taxa commonly found in New Zealand streams.

2 Introduction to *Guidelines*

Of key concern to water managers, iwi, recreationalists, conservationists and the general public are the "instream values" of our rivers. The *Flow Guidelines* (MfE, 1998) define instream values as including:

- ecological values
- aesthetic values (including recreational and landscape values)
- values linked with Maori culture and tradition.

When managing rivers and streams for instream values, it is important to consider periphyton for two reasons: periphyton provides much of the energy for the maintenance of the rest of the ecosystem, right through to fish. Therefore, it is essential that we ensure that a healthy, diverse periphyton community exists if we wish to have a healthy and diverse stream ecosystem. Such attributes are also necessary to meet the cultural expectations of a society increasingly sensitive to environmental quality and sustainable resource use. Second, periphyton can proliferate, forming large nuisance growths of slime. Such growths can interfere with human uses and degrade the habitat for other organisms. While high biomass is a natural phenomenon in many streams at certain times of the year, human activities can easily increase both the size of the growths and the length of time over which they occur in streams.

2.1 Responsibilities under the RMA and the relevance of stream periphyton

Water management in New Zealand is principally controlled by the RMA. Section 5 of the RMA describes its purpose:

1 The purpose of this Act is to promote the sustainable management of natural and physical resources.

2 In this Act, "sustainable management" means managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic and cultural well being and for their health and safety while –

  a Sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and

  b Safeguarding the life-supporting capacity of air, water, soil and ecosystems; and

  c Avoiding, remedying or mitigating any adverse effects of activities on the environment.

Further analysis of section 5 and its meaning can be found in the *Flow Guidelines for Instream Values, Volume A* (MfE, 1998).

Under section 30 of the RMA, functions and powers for water management lie with regional councils. Regional councils may prepare regional plans for water (and other natural and physical resources) to assist with carrying out their functions under the RMA.

This is particularly important for water management, as the restrictions placed on water and the beds of rivers and lakes mean that most activities are prohibited unless they are expressly allowed by a rule in a regional plan or resource consent.

The RMA requires that all components of ecosystems and human needs be addressed. Section 6, on matters of national importance, includes the need to consider and preserve the natural character of rivers and their margins (6(a)) and the protection of areas of significant indigenous vegetation and significant habitats of indigenous fauna (6(c)). Section 7 instructs that particular regard must be taken of the "intrinsic values" of a system (ie, its biological diversity and the essential characteristics which determine an ecosystem's integrity, form, functioning and resilience (7(d)), maintenance and enhancement of the quality of the environment (7(f)) and the protection of trout and salmon (7(h)).

In certain circumstances periphyton can proliferate and become a nuisance and adversely affect water quality for a range of instream values. The RMA provides for waters to be classified in regional plans as an aid to the management of water quality. In recognition of the potential problems created by high-biomass biological growths in streams, the RMA specifies the following standard for waters being managed for aquatic ecosystem purposes, fish spawning, contact recreation, water supply, irrigation and industrial abstraction: "There shall be no undesirable biological growths as a result of any discharge of a contaminant into water" (Schedule III).

These *Guidelines* are intended to assist water managers in carrying out their functions under the RMA and in the application of the standards for water classes in Schedule III. The suggestions presented will allow water managers to more easily identify areas where periphyton has the potential to proliferate, form nuisance growths, and to control such growths.

2.2 Habitat classification, periphyton and the management of streams

Streams and rivers, and the ecosystems they support, are controlled by a hierarchy of physical variables. At the broad scale, different combinations of the ultimate variables of the environment– geology, climate and human activities and the subsidiary outcome of these such as topography, slope, vegetation and land use – are the fundamental controllers of local habitats for stream biota as measured by variables such as depth, velocity, nutrients, etc (Biggs et al, 1990). Different combinations of these variables result in specific types of habitats such as shallow, swift cobble-bed streams with unenriched waters or deep, slow-moving streams with silty beds that may be enriched. Different sets of biota, including periphyton, have evolved to exploit such differences in habitat conditions. Classifying these different habitats using an appropriate set of controlling variables, and defining distinctively different biological communities in these different habitat types, has a number of advantages for water resource management (Biggs et al, 1997b; Snelder et al, 1998):

- setting ISMOs: a framework for assessing human values associated with a particular stream, resolving conflicts between values, then setting management objectives at local and regional levels. Reference to the habitat type also assists in identifying the variables requiring monitoring for achieving the given objectives (eg, nutrient concentrations)
- prediction: community composition and biomass likely to be encountered in areas where information is lacking can be predicted by analogy to similar habitat types where information does exist
- setting conditions in statutory planning: a framework for setting regionally relevant and achievable water quality and biological conditions
- bio-assessment: a basis for comparing and interpreting the state of biological communities, and thus the relative health of stream ecosystems, regionally and nationally such as for state of the environment reporting
- monitoring: to help define reference sites and develop monitoring programmes
- methods: to help decide on sampling methods
- data interpretation: encouraging the development of a holistic approach to river management, highlighting the linkages between physical and biological responses and the need to consider multiple trophic levels.

One of the most important benefits of using physical habitat classification as a basis for evaluating periphyton communities (and indeed stream management in general) is that through the association of specific biological communities with specific habitat types, there is a more objective basis for evaluating potential instream values and then managing public expectations. It is very important that the public's expectations are realistic. However, there are many cases in which they aren't. Habitat classification helps us identify such situations. For example, people might want to have a particular section of a stream managed for recreational fishing, and for this to happen, it might be necessary to eliminate blooms of filamentous algae during summer. However, if the catchment includes a significant proportion of Tertiary marine siltstones which are rich in nutrients, this would be readily detected in the habitat classification. It would then be clear that filamentous algal growths are a natural product of the catchment conditions and clearly impossible to control.

3 Periphyton and their importance in stream ecosystems

3.1 Terms

Periphyton, as noted earlier, is the slime coating objects in streams. Occasionally difficult to detect, periphyton colours submerged objects brown or green (see Figure 3). The term *periphyton* is the most common descriptor in stream ecology for this community. However, other terms are also used, such as *Aufwuchs* (commonly used in Europe), a German description of the community meaning "to grow upon" (Stevenson, 1996a), and *phytobenthos*. The community is composed predominantly of algae and cyanobacteria (previously called "blue-green algae") and so the term *benthic algae* is also used (particularly by algal biologists). The term *periphyton* is adopted for the present guide since it has become the most widely used term in stream ecology.

Figure 3: Thick periphyton slimes on gravels, and mats of filamentous periphyton (*Cladophora*) caught around rocks, in a run of the Waipara River, North Canterbury.

The term periphyton *community* is commonly used throughout the guideline. This denotes a specific group of periphyton taxa. Often the individuals of such groups will not be closely related phylogenetically but have developed traits independently that allow them to coexist in the same habitat. For example, the filamentous cyanobacterium *Phormidium* can overlie communities dominated by diatoms (such as *Cymbella*, *Gomphoneis* and *Synedra*) in slow-flowing habitats of moderately enriched streams in late summer.

Population refers to many individuals of just one species. A major problem in periphyton evaluation is that many of the organisms cannot be identified to species level because, for example, they lack the necessary reproductive structures at the time of analysis. As a result just the generic level name is often only used. This commonly occurs for the filamentous green algae. The term *taxa* (singular: *taxon*) refers to an organism identified to its lowest practical taxonomic level.

While periphyton are present in all streams and rivers, these *Guidelines* will mainly concentrate on communities living in relatively shallow streams/rivers (ie, wadable) which have beds predominantly composed of gravels and cobbles. These are the environments where periphyton impact most on human values and contribute most to aquatic food chains. Such streams are commonly found throughout New Zealand draining areas of foothills and mountains. In lowland areas, or in areas with a very low gradient, streams tend to have low energy, the bed sediments are mainly composed of silts/sands, flow variability is low and primary production in such streams tends to be dominated by larger vascular macrophytes or phytoplankton.

A glossary of terms commonly used in the manual is given in Appendix 1.

3.2 Phylogenetic links and general classification

While most algal taxa in the periphyton obtain their energy for growth through photosynthesis (a distinguishing character of plants), a number of scholars do not consider these organisms to be plants. Indeed, only one Division (the "green" algae) are true plants in the evolutionary sense, whereas another is composed of bacteria and more closely related to animals (popularly known as the "blue-green algae", but more correctly termed *cyanobacteria*) (Lowe and Lalibertae, 1996).

Different groups, or divisions, of algae in the periphyton community are distinguished primarily on the basis of their pigmentation. All divisions have chlorophyll *a*; however, some divisions have other pigments such as *b*, *c*, or *d*. Other accessory pigments such as fucoxanthin may be prominent, and these accessory pigments may give some divisions their distinctive coloration such as in the red algae. There are also important differences in the composition of cell walls and storage products. For a more comprehensive summary of the basis for taxonomic division of periphyton communities and algae in general, see Stevenson (1996a) and Bold and Wynne (1985).

Table 1: Summary of the main divisions of algae found in stream periphyton communities, their morphology and means of motility (after Bold and Wynne, 1985; Stevenson, 1996a) (Mot., motile; N-M, not motile).

Division	Morphology						Means of motility
	Unicellular		Colonial		Filamentous (unbranched and branched)		
	Mot.	N-M	Mot.	N-M	Mot.	N-M	
Cyanophyta (cyanobacteria)		✔		✔	✔	✔	Sheaths
Chlorophyta (green algae)	✔	✔	✔	✔		✔	Flagella, pectin
Bacillariophyta (diatoms)	✔	✔		✔		✔	Raphe
Rhodophyta (red algae)						✔	
Chrysophyta (chrysophytes)	✔	✔	✔	✔		✔	Flagella, pseudopods
Xanthophyta (xanthophytes)						✔	

While the different Divisions of algae comprising stream periphyton communities are mainly distinguished on differences in pigmentation, these are usually accompanied by conspicuous differences in size of filaments, texture, shape of cells etc. This enables the groups to be distinguished in the field with the naked eye or with the assistance of a simple low-powered field microscope. Some taxa are even distinguishable in the field down to the generic level. However, fine-scale identification to genus and species levels is mostly carried out on the grounds of detailed cell size and morphology (eg, morphology of the silica frustules that make up the internal structure of diatoms), branching patterns (eg, some green and red algae), and reproductive structures (eg, cyanobacteria, green algae and red algae). Such characteristics can only be distinguished using detailed microscopy.

Four main morphological types can be distinguished: filamentous unbranched, filamentous branched, unicellular and colonial/multicelled (see technical manual). Most diatoms are unicellular (eg, species of *Navicula*, *Synedra*), a few diatoms and some cyanobacteria are colonial (eg, *Fragilaria*, *Nostoc*), and most green and red algae are filamentous (eg, *Stigeoclonium*, *Audouinella*) (Table 1). Reproductive structures are particularly important in distinguishing different species of filamentous green algae. However, these structures are rarely present (because reproduction is usually vegetative in these taxa), so we are seldom able to characterise communities dominated by filamentous green algae to species level (eg, *Spirogyra*, *Oedogonium*).

Similarly, many species of cyanobacteria are partly distinguished on the basis of characteristics such as the thickness of layers of mucilage surrounding individual filaments, and these are very difficult to discern without special staining and a very high degree of experience (eg, *Lyngbya*, *Phormidium*). The use of size and morphology for separating species and genera presents difficulties (particularly within the diatoms). This is because there is a high degree of variability and many so-called "species" appear to grade into other species depending on the habitat. Even within a given habitat and sample there can be wide variations in size associated with differences in the state of vegetative reproduction. For example, diatoms get progressively smaller as a given population continues to divide until they reach a certain "minimum" size after which sexual reproduction occurs and a group of full-sized individuals can redevelop.

Most of the Divisions have genera that have cells or filaments that move (called "trichomes" in the cyanobacteria) (Table 1). This is an attribute of these communities that is unusual for "plant-like" organisms. Trichomes of *Oscillatoria* can often be seen "gyrating" under the microscope. Some unicellular diatoms are also highly motile. These are mainly raphed forms such as *Navicula* and *Frustulia*. They can move at amazing speed, covering distances many times their body length in minutes (equivalent to approximately 1 m/h) and can be observed while examining virtually any fresh samples under a high-powered microscope (ie, 1000 X magnification). Some larger taxa gather enough momentum to knock other taxa off the substrate. Motility allows these taxa to move up to the surface of the mat in search of light and nutrients and also allows them to burrow down to the base of the mat in times of adversity. Such a facility is very advantageous in sand habitats where it appears that these taxa may actively burrow to evade the abrasive effects of higher water velocities.

3.3 Broad substratum-based community types

A fundamental controller of the nature and general taxonomic composition of periphyton communities in streams is the type of substratum that the community grows on (eg, sand vs. stones vs. weeds etc.; Burkholder, 1996). This is a function of micro-spatial differences in habitat stability (~ disturbance) and nutrient resource supply that vary over small spatial scales in streams. Different groups have evolved specific attributes that enable them to exploit certain combinations of habitat stability and resource supply more successfully. A summary of commonly recognised subgroups of periphyton is given in Table 2.

Table 2: Summary of common subgroups of periphyton based on the nature of the substratum that they colonise (based on Burkholder, 1996; Stevenson, 1996a, S. Moore pers. comm.).

Term	Habitat	Examples of Common Taxa
Epilithon	Hard, inert, substrata such as gravels, cobbles, boulders that are many times larger than the size of the individual	*Ulothrix zonata, Gomphoneis minuta* var. *cassieae, Cymbella, kappii Cymbella minuta, Synedra ulna, Stigeoclonium lubricum*
Epiphyton	Aquatic plants and filamentous algae that are much larger than the epiphytic periphyton taxa. These host plants may be a major source of nutrients.	*Achnanthidium minutissimum, Audouinella hermanii, Chamaesiphon incrustans, Cocconeis placentula, Gomphonema parvulum, Rhoicosphenia curvata*
Episammon	Sand grains that are hard and relatively inert, and generally smaller than most taxa.	*Achnanthidium* spp., *Fragilaria* spp., *Navicula* spp.
Epipelon	Mud and silt grains that are organic or inorganic and smaller than most unicellular taxa.	*Cymbella* spp., *Fragilaria* spp., *Frustulia rhomboides, Navicula viridula, Oedogonium* spp., *Phormidium* spp., *Synedra ulna, Vaucheria sp.*
Metaphyton	Large filamentous algae that are generally not attached to the substrata. Most commonly inhabitants of pools and backwaters.	*Mougeotia* spp., *Spirogyra* spp., *Zygnema* spp.
Epizoic	Residing on the surface of animals such as cases of caddis larvae and shells of snails	*Stigeoclonium* spp., *Gomphoneis minuta* var. *cassieae, Audouinella hermanii*

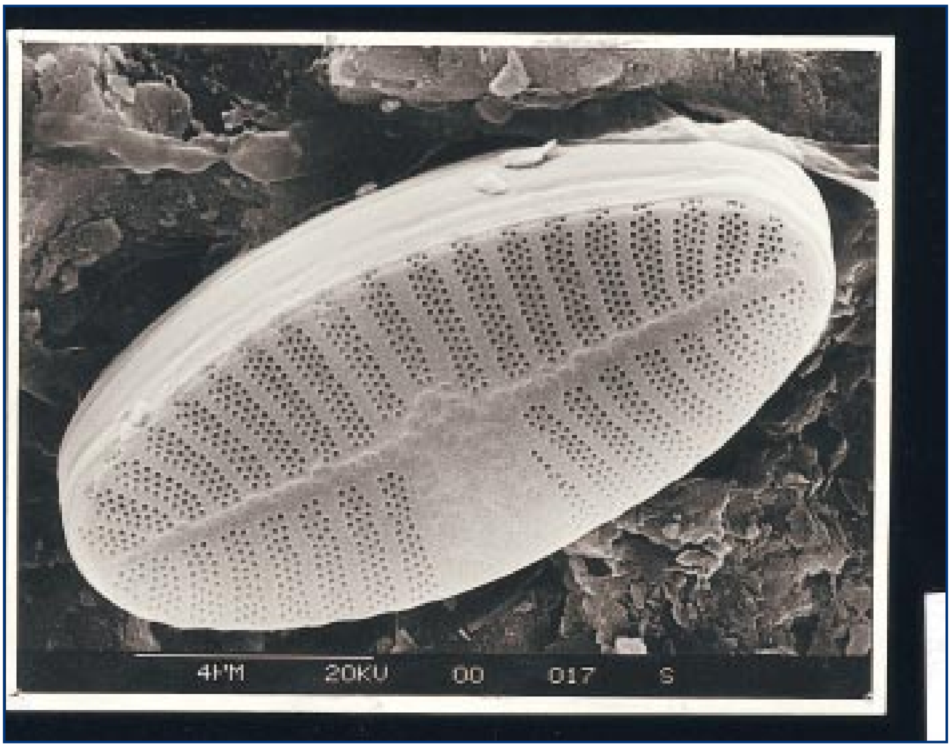
Taxa on rock and larger plant habitats are generally well attached by mucilaginous pads (eg, *Synedra ulna*), as a part of mucilage mounds or balls (eg, *Nostoc*), by mucilaginous stalks (eg, *Gomphoneis*), by specialised holdfast structures (eg, *Ulothrix*), or by entanglement in other well-attached taxa (eg, *Melosira varians*). Taxa dominating sand and mud habitats are often quite motile. Many of these taxa may also be found abundantly among the more firmly attached rock communities. Indeed, several of the rock based taxa are also not particularly specific in their substrate requirements. For example, the filamentous red alga *Audouinella hermanii* is often found on stable boulders and embedded cobbles/gravels, but can also form very conspicuous epiphytic communities on aquatic mosses and submerged willow roots (Biggs and Price, 1987). Similarly, the diatoms *Achnanthidium minutissimum* and *Cocconeis placentula* can be found abundantly in both epilithic and epiphytic habitats.

3.4 The benefits of periphyton in stream ecosystems

As noted earlier, periphyton is the primary transducer of the sun's rays into biologically based energy for stream ecosystems. Thus, this community is the "grass" of streams for aquatic grazing animals. Take the periphyton away and we would often only have barren flow chutes, devoid of insects and fish. In some northern hemisphere forest streams, inputs of palatable leaf detritus can be high (eg, from deciduous trees) and many stream insects have evolved to utilise this energy source. However, in New Zealand this link is less clear and, at least for streams in unforested catchments (probably the majority of our larger streams and rivers), the energetics of ecosystems appear to be more driven by instream "autotrophic production".

A major portion of the periphyton in streams is composed of algae. These algae capture the energy of sunlight via their chlorophyll molecules, absorb carbon dioxide and other nutrients such as phosphorus and nitrogen from the surrounding water, and then synthesise organic carbon in the form of new or enlarged cells. Algae commonly secrete a portion of this carbon, and a host of other organisms then live off this material such as communities of bacteria, fungi and protozoa. Indeed, large algal filaments are often substrates for smaller algal filaments or unicellular algae (Figure 4), and cells which are then substrates for bacteria.

Figure 4: Scanning electron microscope photo of a silica frustule of the diatom *Achnanthidium*. The patterns of pores and etching on the surface are generally identical within a given species and are partly used in identification. A cell like this would normally need to be examined under a high-power microscope at >1000 X magnification to be certain of its identification. This species is widely found throughout the world and can adhere quite strongly to stones and macrophytes in streams. It is not normally associated with proliferations of periphyton.



This micro- and macroscopic assemblage is then grazed by the invertebrates (snails, mayflies, caddisflies, midges etc) that live on the stream bed. These invertebrates usually hide under the stones for much of the day, venturing out onto the rocks to graze the periphyton mat in darkness. Some insects such as midges even burrow into the periphyton and make tube dwellings within the mat.

While few invertebrates appear to have become specialised in grazing certain forms of periphyton, the best periphyton for most invertebrates appears to be composed of diatoms. These are generally high in fats and oils (lipids) and are also easily grazed because they usually only form moderate to thin films on stones. Some invertebrate species appear to avoid some of the large, green filamentous algae. This may be because the diameter of the filaments is too great for the grazers to take into their mouths, these species may have too little food value, or they may have anti-herbivory chemicals that render them unpalatable.

Another important role for periphyton in streams is its ability to improve water quality. Indeed, these communities are cultivated in trickling filters of wastewater treatment plants to remove pollutants and polish effluent prior to discharge. In shallow streams, natural periphyton communities act in a similar way. They have a high capacity for removing nitrogen and phosphorus from stream waters, and the bacterial communities within mats have a great ability to remove organic contaminants (eg, from farm stock and surface runoff from the land). This process then makes the water much more useable for other purposes such as stock drinking supplies. The contaminating nutrients, accumulated as periphyton biomass, are often flushed out of the stream system during floods.

3.5 Values affected by nuisance growths

Problems associated with excess biomass accumulation (*nuisance growths)* tend to become most prominent during low flows (Figure 5) and thus tend to be sporadic. Some common stream-related values that may be compromised by periphyton proliferations, and the associated problems, are listed in Table 3. The extent of the annoyance created by proliferations to aesthetic appreciation, angling, contact recreation such as swimming, and whitebait fishing is very subjective and likely to vary greatly among individuals and also as a function of the type of stream environment. The effects on water quality and ecosystem degradation are only moderately well quantified, and a number of cause-effect assumptions in this linkage need careful testing. Shifts in benthic community structure are clearly apparent across a range of enrichment regimes (see Section 8.1), but specific links between the abundance of many of the common invertebrate taxa and periphyton biomass have not been developed. Indeed, this may be difficult to do because of the degree of interaction between periphyton biomass and other variables.

Figure 5: An aesthetically undesirable proliferation of filamentous green algae (mainly *Oedogonium* species) in a shallow gravel-bed river during summer low flows downstream of intensive agricultural development (Hakataramea River, North Otago). Enriched groundwater appeared to be entering the reach.

Clogging of intake structures for water abstraction is a common problem. This usually necessitates more regular, sometimes daily, maintenance of structures.

Table 3: Instream values that can be compromised and associated problems that may arise as a result of periphyton proliferations (based on MfE 1992 and Biggs, 2000).

Instream Value	Problem
Aesthetics	Degradation of scenery, odour problems
Biodiversity	Loss of sensitive invertebrate taxa through habitat alteration, possible reduction in benthic biodiversity
Contact recreation	Impairment of swimming, odour problems, dangerous for wading
Industrial use	Taste and odour problems, clogging intakes
Irrigation	Clogging intakes
Monitoring structures	Fouling of sensor surfaces, interferes with flow
Potable supply	Taste and odour problems, clogging intakes
Native fish conservation	Impairment of spawning and living habitat
Stock and domestic animal health	Toxic blooms of cyanobacteria
Trout habitats/angling	Reduction in fish activity/populations, fouling lures, dangerous for wading
Waste assimilation	Reduces stream flow, reduces ability to absorb ammonia, reduces ability to process organics without excessive DO depletion
Water quality	Increased suspended detritus, interstitial anoxia in stream bed, increased DO and pH fluctuations, increased ammonia toxicity, very high pH
Whitebait fishing	Clogging nets

Figure 6: Plume of filamentous green algae (*Spirogyra*) streaming from a groundwater upwelling at the side of a gravel-bed stream (Makara Stream, near Wellington).

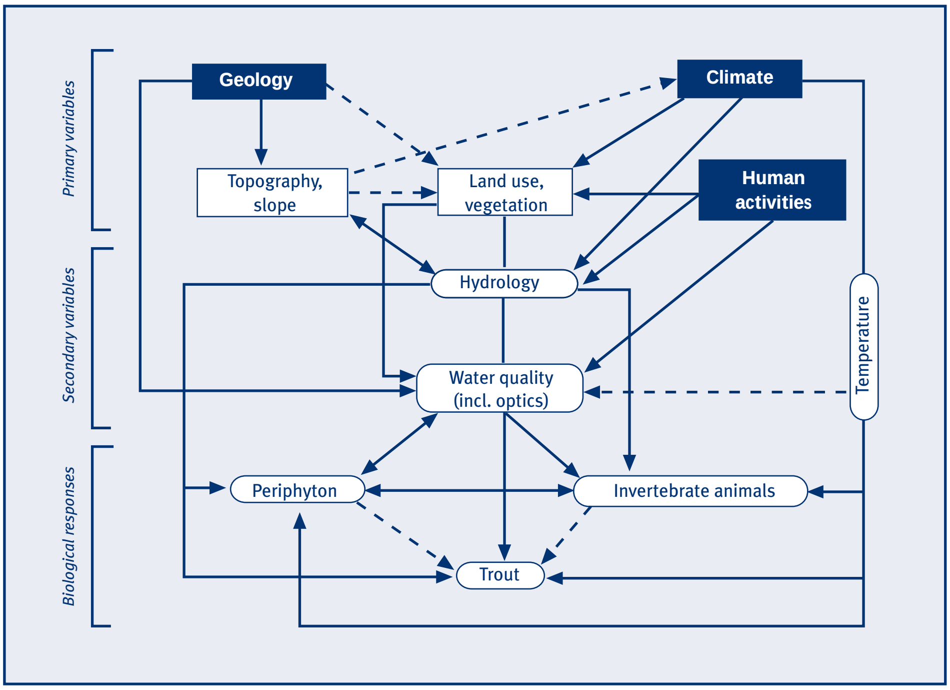
4 Review of factors most commonly controlling periphyton growth and accumulation in streams

The following chapter reviews community processes and causal linkages as a basis for better understanding the potential effects of human activities on periphyton and criteria for the control of proliferations. Where possible, New Zealand examples are used to illustrate points.

4.1 The hierarchy of environmental controllers

The local factors controlling biomass and type of periphyton existing at any given point in a stream, and at any given time, are the result of what can best be described as a hierarchy of environmental controllers. At the top are the primary, or ultimate, variables of the habitat, variables that can't be changed by humans: catchment geology and climate, including precipitation and temperature (see Figure 7). These features, and human activities, set the overall context for the landscape (topography/slope and land use/vegetation) which then cascade down another scale to control aspects of the habitat of more immediate influence to periphyton such as flow regimes, water quality, temperature and the density and type of other biota that may interact with periphyton such as grazing invertebrates. It is these secondary, or proximate, variables that can often be influenced and managed by humans. Aspects of the flow regime which exert a particularly important control on periphyton include the frequency of flood events and duration of stable (low) flows in summer. Aspects of water quality which are particularly important are the concentration of plant nutrients (phosphorus and nitrogen). Both the extent (and intensity) of summer low flows and nutrient concentrations can be strongly influenced by human activity through changes in land use and hydrology.

Figure 7: A summary of the hierarchy of controllers of periphyton development and composition in streams. Strong causal effects are shown as solid arrows and weaker interactions are shown as dashed arrows. Double arrows indicate feedback relationships. Not all conceivable interactions are shown. For example, land use affects periphyton apart from through nutrients, notably with regard to riparian shading, but this interaction is not shown (modified from Biggs et al, 1990 with permission from *New Zealand Journal of Marine and Freshwater Research*).

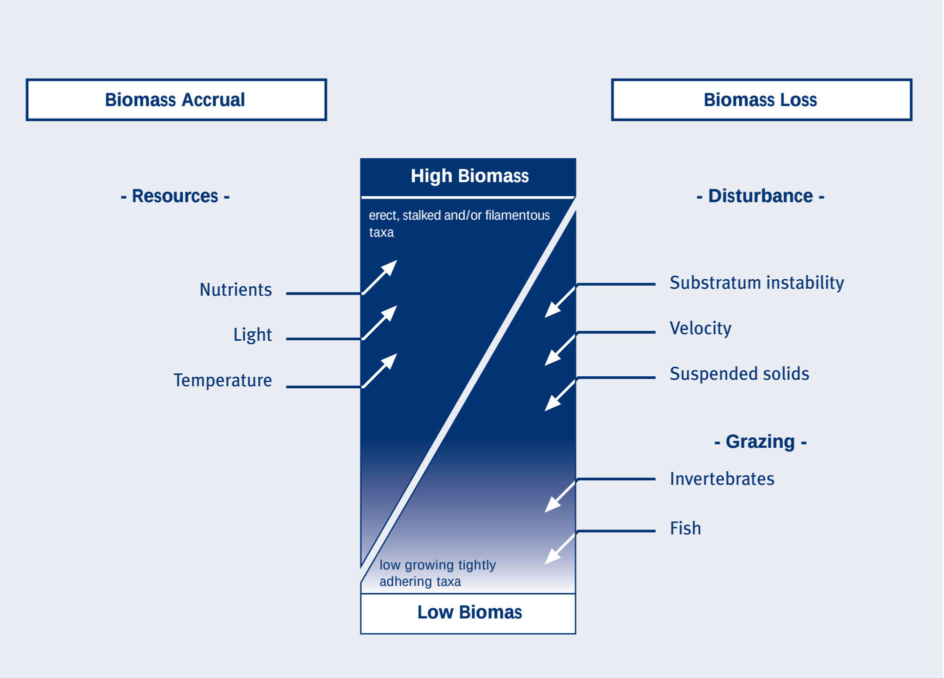


4.2 Overview of processes generating patterns in time and space

Broad-scale spatial patterns are a result of time averaging of short-term time patterns in environmental controllers and natural variability in the life cycle of communities. In general, it is a trade-off between the periphyton's attempt at growing (biomass accrual) and the continual losses that the community suffers along the way (see Figure 8).

The rate of biomass accrual is dictated by the rate of division of cells on the substrate. This in turn is controlled by the supply of resources (nutrients and light) and temperature. Phosphorus, nitrogen, carbon (from dissolved carbon dioxide in the water) and light provide the energy and basic building blocks necessary for photosynthesis and cell growth to proceed. Shortages in any of these materials, or shortages in light energy, can limit the rate at which cells divide. When these become adequate to fully meet community demands (that is, when there is both "nutrient saturation" and "light saturation"), then temperature becomes the next most important controller of how fast the cells divide and the mat biomass develops (Figure 8). This is because the rates of many metabolic processes are highly dependent on temperature (DeNicola, 1996). Temperature also interacts with nutrient supply at sub-saturating levels, through an alteration in metabolic and energy pathways (DeNicola, 1996). However, this interaction is very complex. The effects are unlikely to be clearly distinguishable from other controllers of periphyton biomass accrual in natural stream systems.

Figure 8: Summary of the counteracting processes of periphyton biomass accrual and biomass loss, and the principal local factors contributing to these processes, in a stream. Triangles in the central rectangle show relative balance of "biomass accrual" and "biomass loss" The growth form of the communities likely to dominate each end of the accrual – loss gradient is also shown (reproduced from Biggs, 1996a with permission from Academic Press).



Biomass loss occurs by two main processes. First, physical events such as flooding (and associated high water velocities, substratum instability, suspended solids abrasion) cause punctuated losses from the community (called "disturbances"). The amount of biomass lost varies greatly depending on the intensity of the event (ie, how fast the water flows, how unstable the bed sediments are) and how resistant the communities are to increases in water velocity and sand or gravel abrasion. Intense floods (say, with a 0.5–1 year return period) are generally catastrophic events for the periphyton, no matter what the nature of the community is. On the other hand, the outcome of small to intermediate-sized floods (more appropriately called "freshets") that may only result in partial mobilisation of the bed sediments are much more difficult to determine. For such events, the degree to which the periphyton community can resist being torn from the bed ("sloughing") has a major bearing on the degree of community disturbance.

As could be expected from the way different terrestrial vegetation is affected by wind storms, communities composed of low-growing taxa (ie, low biomass) such as some diatoms (*Achnanthidium*, *Cymbella*, *Cocconeis*, *Synedra*) and taxa with strong attachment structures (eg, *Stigeoclonium lubricum* and *Ulothrix zonata*) are much less affected by freshets than communities composed of tall (ie, high biomass) and loosely adhering species (*Melosira varians*, *Spirogyra* spp., and *Cladophora glomerata*) (see Peterson, 1996, for a recent review of disturbance processes in periphyton). Thus, depending on what was growing at a site prior to a freshet, there could be quite different outcomes in terms of disturbance to community form and functioning. Biggs and Thomsen (1995) pointed out that because periphyton growing in oligotrophic streams usually form thin film communities of low biomass, these communities will be less prone to disturbance by freshets than the higher biomass, often filamentous communities, normally dominating eutrophic streams.

Losses by grazing are also potentially highly variable and depend on the density and type of invertebrate grazers present and the growth rate of the periphyton (reflecting nutrient and light supply, and temperature). In New Zealand streams not prone to frequent flooding, invertebrate communities are often dominated by snails (particularly *Potamopyrgus antipodarum*), with sub-dominant populations of caddisfly larvae and mayfly larvae (Quinn and Hickey, 1990). With increasing flood disturbance frequency, snails tend to be eliminated, then caddisfly larvae. In highly flood-prone streams, mayflies usually dominate (Sagar, 1986; Scarsbrook and Townsend, 1993; Biggs et al, 1998d; Holomuzki and Biggs, 1999).

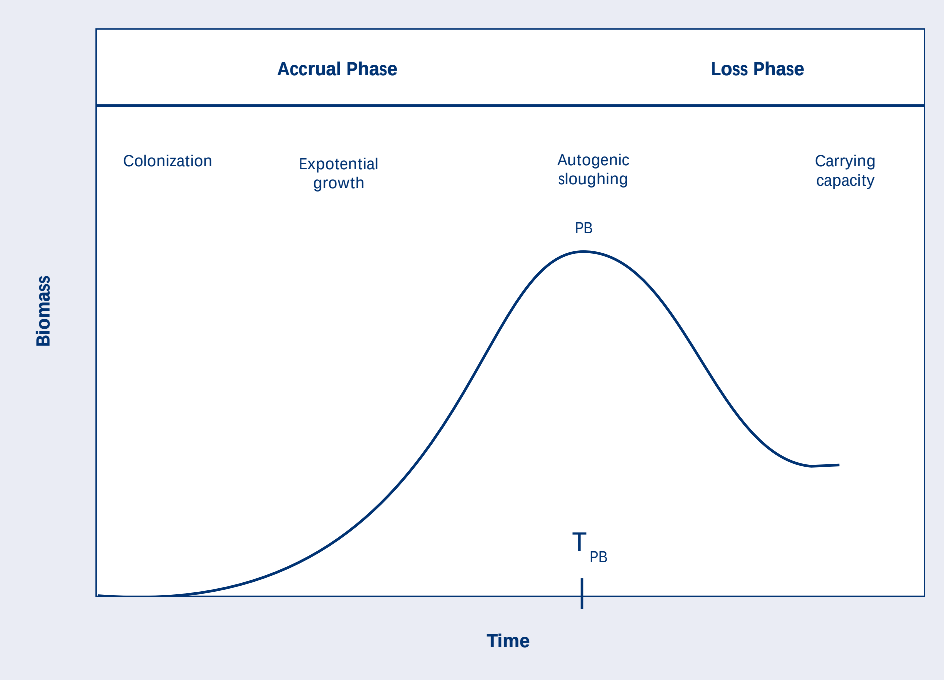
This also appears to create a gradient in grazing efficiency, because *Potamopyrgus* tends to be a more aggressive grazer than caddisflies, which, in turn, appear to be more aggressive grazers than mayflies in New Zealand streams (Biggs et al, 1998d). If there is only a low density of grazers (eg, caused by a lack of suitable refugia, such as on bedrock) then periphyton biomass accrual can proceed largely unconstrained and proliferations may develop. Another example of this is a phenomenon that has been observed in a number of gravel-bed streams, where periphyton biomass often accrues fairly rapidly (and to high levels) after a major flood during a window of opportunity while there are still few invertebrates present (invertebrates take much longer to colonise and reproduce than periphyton) (Scrimgeour and Winterbourn, 1989; Biggs and Stokseth, 1996). After several months, invertebrate densities can catch up and appear to control periphyton biomass accrual providing that the rate of production is not high. Overall, grazing activity is likely to most significantly control periphyton production in physically stable environments (Steinman et al, 1991). Steinman (1996) provides a comprehensive review of grazing effects on freshwater periphyton.

4.3 Time patterns

4.3.1 Short term

Severe flood disturbances tend to reset community accrual so that a new cycle of colonisation by "pioneer" or "ruderal" taxa begins, followed by exponential growth and a succession toward the slower colonising over-storey "competitive" taxa (Fisher et al, 1982; Biggs and Stokseth, 1996). Accrual of biomass through a combination of immigration/colonisation and growth tends to dominate early in the sequence (the "accrual phase"), but then a shift to dominance of loss processes through death, emigration, spontaneous sloughing, and grazing occurs later in the sequence (the "loss phase") (Figure 9) (Biggs, 1996a).

Figure 9: An idealised short-term periphyton accrual cycle after major flooding. PB (peak biomass) = maximum accrual cycle biomass; T_{PB} = time to PB from commencement of colonisation (reproduced from Biggs, 1996a with permission from Academic Press).



The rate of recolonisation after a flood is highly affected by local velocities close to the stream bed as well as the densities of cells being washed down from upstream areas not affected, or less affected, by flood disturbance (refugia). Settlement of these immigrants tends to be inhibited by high velocities and enhanced by low velocities (Stevenson, 1983). Initial pioneer taxa are usually diatoms (which tend to have rapid growth rates) such as *Achnanthidium*, *Cymbella*, *Gomphoneis* and *Synedra*. A variable successional trajectory can occur from this point depending on nutrient supply regimes.

In unenriched (ie, oligotrophic) habitats, the climax communities (generally those at peak biomass) tend to become dominated by a film of diatoms with patches of filamentous red algae (eg, *Audouinella hermanii*) on very stable substrata and prostrate filamentous cyanobacteria tolerant of low nutrient levels (eg, *Calothrix*, *Tolypothrix*). In moderately enriched (ie, mesotrophic) habitats, the climax communities tend to become dominated by moderately tall growing filamentous green algae (eg, *Oedogonium*, *Stigeoclonium*), large stalked diatoms such as *Gomphoneis minuta* var. *cassiae* and several prostrate cyanobacteria (*Phormidium*, *Schizothrix*). In enriched (ie, eutrophic) habitats, the climax communities tend to become dominated by tall-growing filamentous green algae (eg, *Cladophora*, *Rhizoclonium*) and/or the filamentous diatom *Melosira varians*.

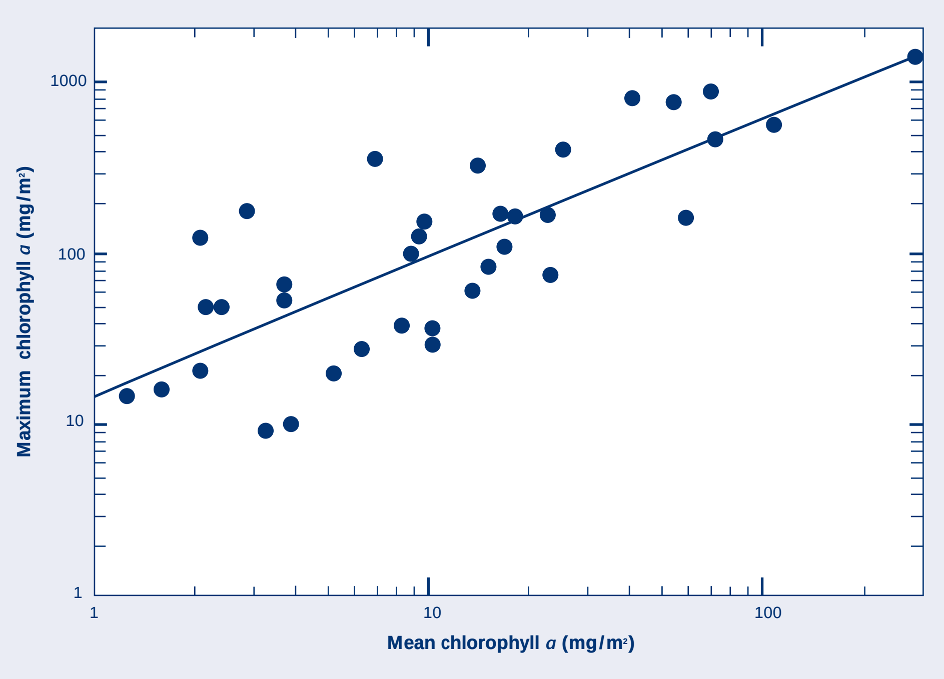
In some streams and rivers (particularly during low flows in non-glacial mountain and glacial mountain-fed rivers), certain diatom taxa colonise the stream bed and monopolise it through until peak biomass, so that a succession of taxa is prevented (eg, *Gomphoneis minuta* var. *cassieae*, *Cymbella kappii*, *Synedra ulna*) (Biggs et al, 1998d). A more extensive classification of the trophic preferences of taxa commonly found in New Zealand streams is given in Sections 6.1 and 7.6.

4.3.2 Nutrient supply control of peak and mean periphyton biomass in streams

Unlike lakes, there is very high temporal variability in algal biomass in rivers. For example, Dodds et al (1998) found a ratio of peak to mean seasonal biomass of 4.52 in 176 stream sites of North America and New Zealand, compared with a ratio of 1.7–2.6 for lakes. A ratio of 10 is apparent if only New Zealand streams are considered (Figure 10), illustrating the very high variability of periphyton communities in New Zealand streams. Periods of high biomass may only last for less than two weeks in many streams (particularly those that are unenriched; see Biggs and Close, 1989).

As enrichment increases, the duration of periods with high biomass tends to become longer if flood disturbances are infrequent (eg, 6–8 weeks; see Fig. 6 of Biggs, 1995). For water resources management, and indeed managing the enrichment of streams, it is these periods of peak biomass that are most important. In theory, peak biomass should be strongly related to the concentration of nutrients in the water. Indeed, this link between biomass and nutrient supply regime is at the heart of managing eutrophication in streams so will be discussed in some detail below.

Figure 10: Maximum recorded chlorophyll *a* biomass (~ peak biomass) versus mean monthly biomass of periphyton for 12–15 months of sampling at 30 New Zealand stream sites covering a wide range of enrichment (data derived from Biggs, 2000). Best-fit regression equation is: $\log_e$ peak chlorophyll *a* (mg/m^2) = 2.745 + 0.797 x $\log_e$ (mean monthly chlorophyll *a*), $r^2 = 0.668$, N = 30.



In practice, linking periphyton biomass to stream nutrient concentrations is very difficult. This is because of:

- the dynamic nature of biomass accrual and loss processes
- the concentrations of dissolved nutrients measured in solution mainly reflecting nutrients that are left over after the periphyton have removed what they need and not the supply concentration
- the difficulty of isolating seepage and groundwater upwelling zones to quantify the local supply of nutrients to periphyton on the stream bed.

If the concentrations of soluble nutrients are high, then we can be certain that the potential exists for high periphyton biomass. However, many situations exist where summer soluble nutrient concentrations are quite low, but a high biomass of periphyton has developed. This occurs most frequently in shallow, cobbly streams (Biggs, 1995).

In an effort to better understand nutrient supply–periphyton biomass relationships, and develop predictive equations for management purposes, five different approaches have been used. These relate biomass to:

- conductivity of the water–a surrogate for the supply of dissolved nutrients which is highly correlated with periphyton biomass and community composition (Biggs and Price, 1987; Biggs, 1988a, 1990a, 1995)
- additions of nutrients to experimental streams (Horner et al, 1983, 1990; Bothwell, 1989)
- average concentration of soluble nutrients over growing periods after floods (Biggs and Close, 1989)
- periphyton mat nutrient concentrations (Biggs, 1990b, 1995)
- water total nutrient concentrations (Biggs and Close, 1989; Dodds et al, 1997).

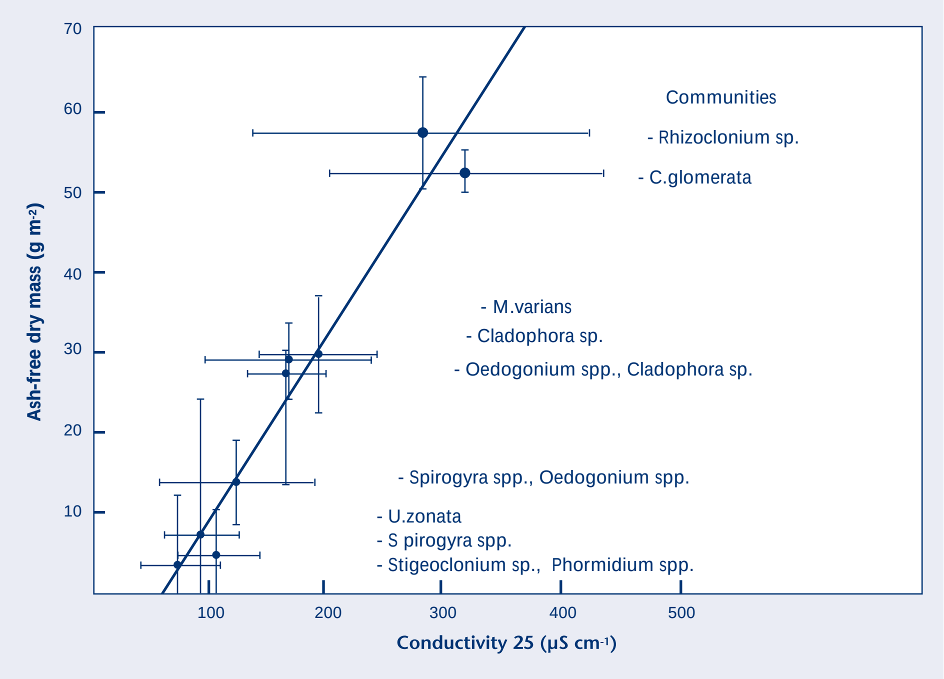
The first three of these approaches are of most relevance to water managers in New Zealand and will be discussed further in the following sections.

In New Zealand extensive use has been made of conductivity as an indicator of background nutrient supply regimes in streams that drain catchments dominated by greywacke, schist, mudstones and granites. Ions that are not heavily used by periphyton, such as calcium, sodium, magnesium etc, appear to be leached from rocks and soils in proportion to nutrients that may limit growth (eg, phosphorus). These ions remain in the water even though the nutrients that have been leached out of the rocks and soils with them may have been taken up by ther periphyton, thus giving an indication of the nutrient supply regime.

Highly significant correlations have been found between periphyton biomass and conductivity in many broadscale studies of periphyton in New Zealand streams (Biggs, 1988a, 1990a, 1995; Biggs and Price, 1987). One of these is displayed in Figure 11. Biggs (1990a) used this relationship, together with results from 100 other New Zealand streams sampled in summer, to determine that streams with a conductivity of <10 mS/m generally have low peak biomass in summer (ie, <20 g AFDM/m^2), streams with a conductivity of 10–20 mS/m have moderate peak biomass (20–40 g AFDM/m^2), and streams with a conductivity of >20 mS/m generally have high peak biomass (>40 g AFDM/m^2).

While conductivity is a very useful, relative, measure of enrichment in streams, and thus good for classification and planning purposes, it has two major limitations. Firstly, in areas with geology that is very high in certain mineral compounds (eg, some volcanic rocks high in sulphur) or catchments near the coast that might be subjected to salt spray, the conductivity–nutrient ratio breaks down and much higher nutrient supply may be indicated than occurs. Secondly, conductivity cannot be used for predictions when assessing the potential effects of nutrient discharges to streams. In such situations, inflow soluble nutrient concentrations are required.

Figure 11: AFDM biomass of nine filamentous periphyton communities related to conductance (standardised to 25°C) of the water in 400+ New Zealand streams during summer low flows. The error bars are 1 s.d. (*C. glomerata* = *Cladophora glomerata*, *M. varians* = *Melosira varians*, *U. zonata* = *Ulothrix zonata*) (reproduced from Biggs and Price, 1987 with kind permission from the *New Zealand Journal of Marine and Freshwater Research*).

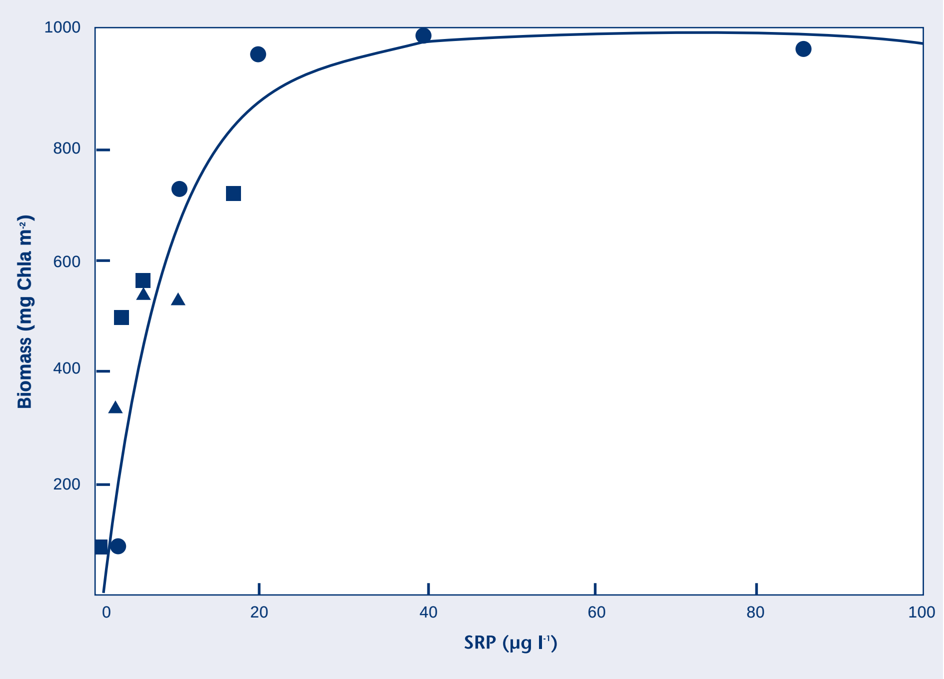


A number of experiments have been carried out to determine the relationship between dissolved nutrient supply rates and periphyton peak biomass. In one of these studies, Bothwell (1989) identified that the nutrient – peak biomass relationship for a diatom dominated community was asymptotic with biomass development saturating at 25 mg added PO_4–P /m^3. This means that the diatom communities probably have a maximum biomass (measured by Bothwell at around 350 mg/m^2 chlorophyll *a*), after which higher nutrient supplies appear to have no effect. Indeed, most field results for diatom-dominated communities in New Zealand streams have found peak biomass values <400 mg/m^2 chlorophyll *a* (Biggs, 1990a, 1995; Biggs and Hickey, 1994).

However, experimental studies with other communities indicate that there could be differences in nutrient supply concentrations at which different communities will saturate. For example, Walton (1990) found that peak biomass in a mixed diatom/ *Phormidium* (cyanobacteria) community saturated at 1000 mg chlorophyll *a*/m^2 with a phosphorus supply concentration of nearly 20 mg soluble reactive P/m^3 (SRP) (Figure 12). However, Horner et al (1990) found that a filamentous green algal community (dominated by *Mougeotia*) grown in the same experimental channels as Walton used saturated with a peak biomass of 350 mg chlorophyll *a*/m^2 at a phosphorus supply concentration of ~ 7 mg /m^3 SRP. This biomass level is much lower than recorded for communities dominated by filamentous green algae in New Zealand eutrophic streams, where chlorophyll *a* can exceed 1200 mg/m^2 (Biggs, 1995).

Velocity is also very important in the determination of peak biomass and will be discussed in more detail in Section 4.4.2.

Figure 12: Peak biomass in diatom/*Phormidium*-dominated communities as a function of phosphorus supply concentration (as soluble reactive P) on natural rocks in artificial streams after three weeks. Biomass scale is in 200 mg chlorophyll *a*/m^2 increments (reproduced from Welch, 1992 with kind permission from Kluwer Academic Publishers).

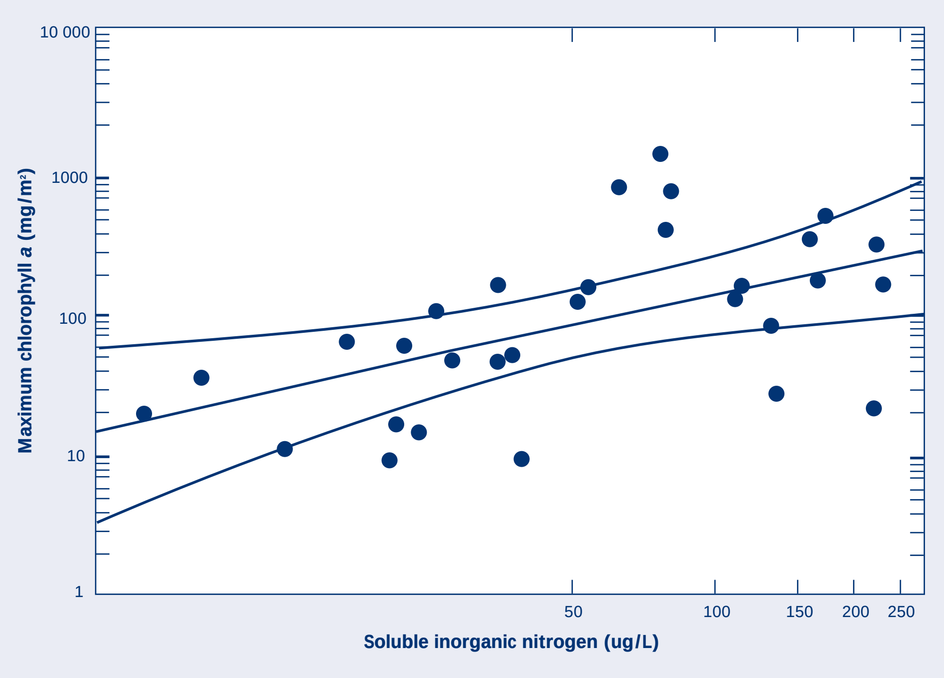


A second important contribution from Bothwell's research was the finding that nutrient limitation of stream periphyton communities occurs at two different scales (representing different processes): the cells at the mat surface and the cells in the rest of the mat. Firstly, the growth of individual cells on the surface of the mat may rarely be limited by a lack of available nutrients in streams. This is because movement of water can decrease the thickness of the nutrient depleted laminar boundary layer around cells and filaments ensuring rapid delivery and better uptake of nutrients. For example, in his experimental streams, Bothwell (1989) found that specific growth rates of periphyton cells were only nutrient limited when phosphorus concentrations were <1 µg P/L. However, as the cells progressively accumulate on the substrate to form a mat, then the cells on the surface absorb most of the available nutrients and the cells at the base of the mat become nutrient starved and eventually die. The mat then becomes unstable and sloughs.

The important point here is that, with higher nutrient supplies, thicker layers of cells can develop before the cells at the base die (and the mat sloughs). This is because the cells at the surface are nutrient saturated for longer periods and higher rates of molecular diffusion occur which maintain cells for longer at the base of the mat. Thus, while growth rates of cells on the surface of the mat may be nutrient saturated at quite low nutrient concentrations in flowing waters, high nutrient supplies are required to develop thick mats.

While the artificial stream experimental studies have advanced our understanding of nutrient supply–biomass processes, there is still a gap to predicting biomass from nutrient supply concentrations in natural streams (because of the difficulty in quantifying nutrient supply). One of the difficulties has been the lack of comprehensive data from streams where a full range of nutrient and biomass parameters have been measured frequently (eg, monthly or more) for long enough. Several data sets have recently been generated from New Zealand streams that may assist in resolving this issue (Biggs, 2000). Figure 13 illustrates a relationship between maximum recorded (~ peak) chlorophyll *a* as a function of mean monthly soluble inorganic nitrogen concentrations from this data. While there is some scatter, the relationship is highly significant (p <0.001).

Figure 13: Maximum chlorophyll *a* as a function of mean monthly soluble inorganic nitrogen concentrations in 30 New Zealand streams (modified from Biggs, 2000 with permission from the *Journal of the North American Benthological Society*).



4.3.3 Time taken to reach peak biomass after a flood

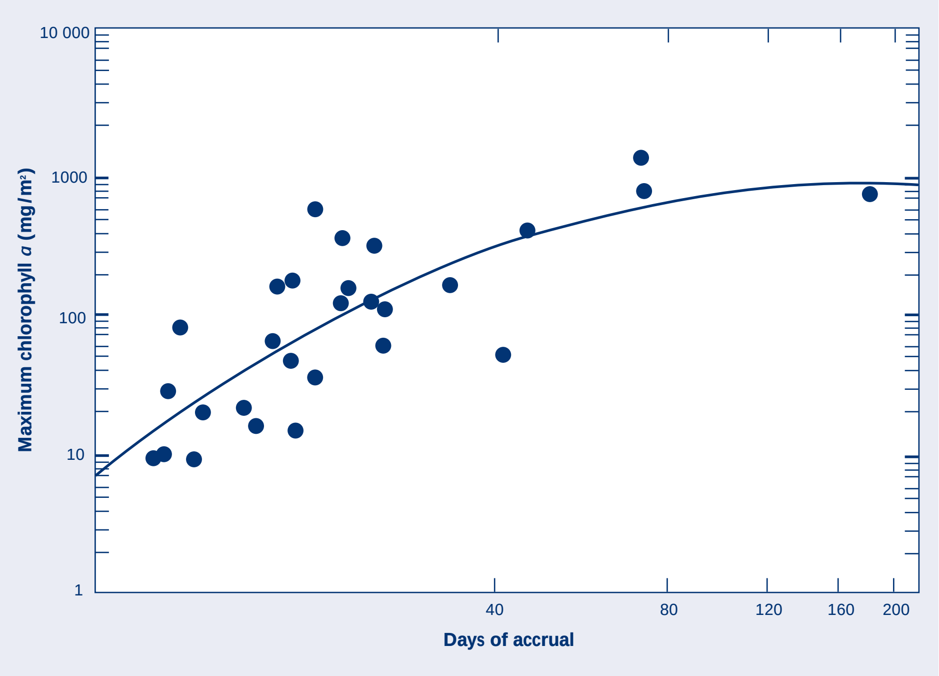
The time taken to reach peak biomass can be a critical question if, for example, it is important to know when irrigation intakes are likely to become clogged with filamentous algal debris or plans need to be made for cessation of abstraction if low velocities are contributing to proliferation problems. Intuitively, we could expect time to peak biomass to be shorter in eutrophic streams because communities can grow faster with higher nutrient supplies. However, this does not necessarily occur. This is because it appears that under severe nutrient limitation the base of the accruing mat dies off very early in the cycle (because of nutrient starvation) and then the whole mat sloughs.

While a reasonably clear "ideal" accrual curve is depicted in Figure 9 and can often be measured using artificial substrata, growth dynamics are often more complicated in natural streams. In particular, our ability to detect such short-term trends is dependent on the scale of sampling. If only a few points on the stream bed are sampled on consecutive occasions, then a high degree of variability will be recorded (associated with spatial variations in velocity or grazing) and a generalised accrual curve may not be evident. Conversely, sampling over a wide area that, say, includes different habitat units within a reach can incorporate communities at very different stages of accrual because of different growth rates and this can mask clear accrual dynamics. Therefore to determine habitat specific parameters for accrual dynamics (such as accrual rate and time to peak biomass), multiple whole substratum sampling is necessary within habitat units such as runs or riffles (Biggs, 1996a).

The time to peak biomass may also be affected by the size (ie, intensity) of the last flood event. Really intense events tend to remove more biomass from the stream bed (Grimm and Fisher, 1989; Biggs and Thomsen, 1995) which, in turn, reduces the availability of propagules to recolonise a stream and thus slows regeneration. The converse is also true. Temperature is also an important factor influencing growth rates. Generally, if nutrients are sufficient then cellular growth rates will be much higher with higher temperatures (eg, respiration rates can double for a 10°C increase in temperature). Thus, time to peak biomass can vary from less than two weeks (Stevenson, 1990) to >12 weeks (Biggs and Stokseth, 1996), and it is very difficult to predict how long this regeneration will take with our current state of knowledge.

Time available for accrual is also critical for determining mean and maximum periphyton biomass in streams. After a 14-month study of nine rivers in Canterbury, Biggs and Close (1989) concluded that flood frequency (which determines accrual time) was at least as important as nutrients in determining periphyton biomass in the rivers. A recent analysis (Biggs, 2000) of data from 30 New Zealand streams has confirmed the finding of Biggs and Close (1989). Indeed, 61.8 percent of the variance in peak biomass was explained just by mean days of accrual (determined as the mean number of days per year between flood events exceeding 3 x median flow) (Figure 14).

Figure 14: Maximum chlorophyll *a* concentrations as a function of mean days of accrual in 30 New Zealand rivers sampled every 2–4 weeks for at least 13 months (modified from Biggs, 2000 with permission from the *Journal of the North American Benthological Society*).



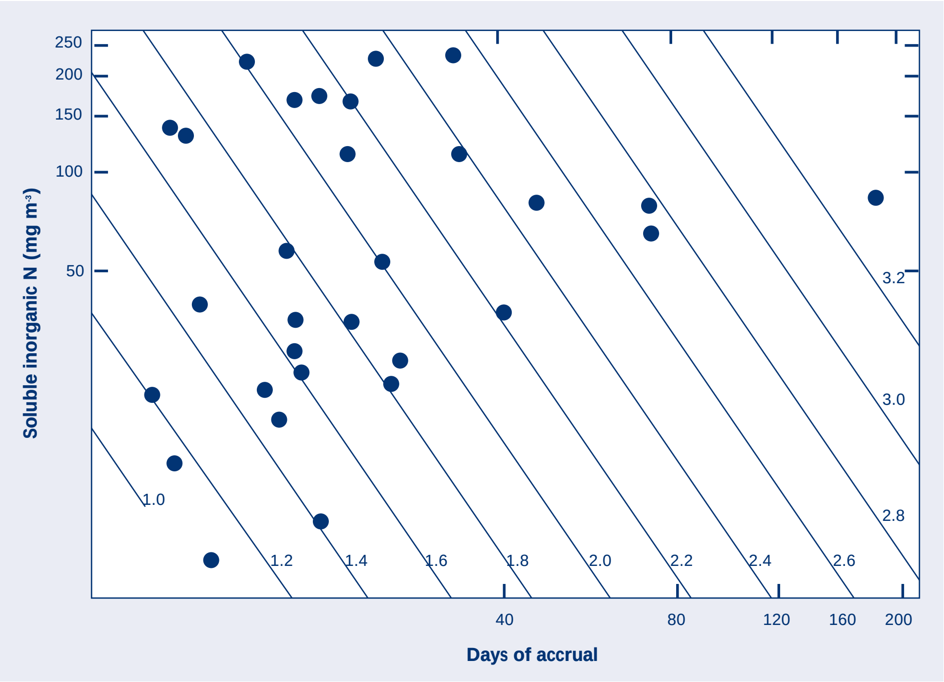
A refinement of the relationship depicted in Figure 13 is therefore possible by including a term to account for the period of growth. A regression model combining days of accrual with mean monthly soluble nutrient concentrations explained 74.1 percent of the variance in peak chlorophyll *a* among the 30 sites. The multiple regression equations for both nitrogen and phosphorus are:

$$\mathrm{Log}_{10}\,(\text{maximum chl. a}) = 4.285 \times (\mathrm{Log}_{10}\,\text{days of accrual}) - 0.929 \times (\mathrm{Log}_{10}\,\text{days of accrual})^2 + (0.504 \times \mathrm{Log}_{10}\,\text{SIN}) - 2.946 \qquad r^2 = 0.741 \qquad (1)$$

$$\mathrm{Log}_{10}\,(\text{maximum chl. a}) = 4.716 \times (\mathrm{Log}_{10}\,\text{days of accrual}) - 1.076 \times (\mathrm{Log}_{10}\,\text{days of accrual})^2 + (0.494 \times \mathrm{Log}_{10}\,\text{SRP}) - 2.741 \qquad r^2 = 0.721 \qquad (2)$$

where SIN is soluble inorganic N, SRP is soluble reactive P, and chlorophyll *a* is in mg/m^2 and soluble nutrients are in mg/m^3. The SIN – chlorophyll relationship is depicted as a contour diagram in Figure 15 and confirms (what we would intuitively expect) that peak biomass increases with increasing time available for accrual and increasing average soluble nutrient concentration.

Figure 15: Log$_{10}$ of maximum chlorophyll *a* (mg/m^2) as a function of mean soluble inorganic nitrogen concentrations and days of accrual (duration of stable flows). Calculated from Equation 1.



4.3.4 Long-term patterns of periphyton development in streams

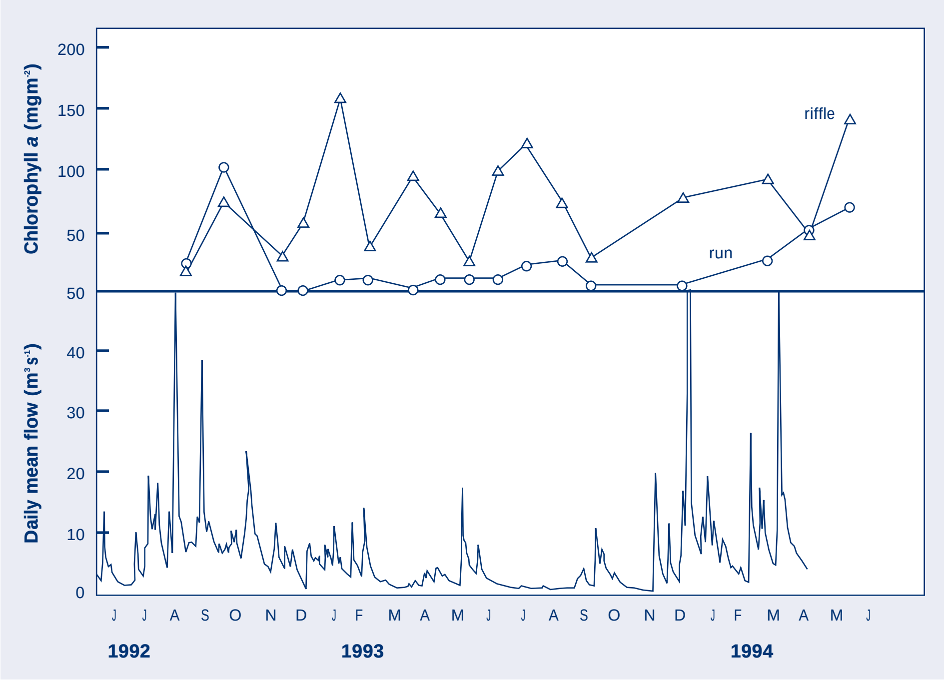
Long-term patterns (ie, covering periods of 2–15 months) in the temporal dynamics of periphyton biomass and community composition in streams tend to reflect the outcome of frequency of flood disturbances and its interaction with nutrient and light supply regime (Biggs 1996a; Young and Huryn, 1996; Biggs et al, 1998b, d). Three main patterns in biomass are evident.

1. There is relatively constant, low biomass throughout the year. This can occur for three main reasons. Firstly, floods may occur so frequently (eg, every 7–10 days such as in some mountain regions) that biomass never gets a chance to accrue to conspicuous levels. Secondly, light and/or nutrient resource supplies may be so low that regeneration between floods is minimal. Thirdly, there may be few flood events, which allows high densities of invertebrates to develop; these then heavily graze the periphyton, thus preventing significant accumulations from developing. The sparse communities that do exist in such streams tend to be dominated by grazing-resistant diatoms such as *Achnanthidium* and tightly adhering cyanobacterial crusts.

2. There are cycles of accrual and sloughing in streams with a moderate frequency of flood events and at least moderate supplies of nutrients and light. Extended periods of flow stability (4–10 weeks) allow biomass to develop with a succession in taxonomic structure (sometimes through to dominance by filamentous algae). Even minor floods can truncate these successions and associated biomass development. In most New Zealand streams and rivers, "ideal" accrual-sloughing sequences are difficult to show because at certain times flood events occur very frequently and once the biomass is low further floods stop re-growth. Thus, it is more common to find parts of the year when biomass is consistently low because of repeated events and parts of the year when biomass is much higher because flood events are few (Biggs et al, 1998b).

   The occurrence of repeated events may be seasonal in some streams, but in many New Zealand streams blocks of repeated events can occur (eg, West Coast streams during El Niño years) resulting in extended periods of low community development. Conversely, if there are prolonged periods of stable flows, then biomass will accrue and autogenic sloughing commence. A temporal sequence of biomass and stream flows from the Kakanui River, Otago, that exhibits such variations in the accrual-sloughing sequence is depicted in Figure 16. This graph shows that sloughing occurred with a moderate flood between October and November 1992 followed by a sequence of accrual during the relatively low flows from November 1992 to January 1993. Sufficient biomass developed during that period to be sensitive to (and sloughed by) a relatively small flood. A prolonged period of low flow from early June through to late September 1993 saw a period of accrual followed by autogenic sloughing.

Figure 16: Temporal variations in chlorophyll *a* (for a riffle community) and stream flows in the lower Kakanui River, North Otago (reproduced from Biggs et al, 1998b with permission from *Archiv fūr Hydrobiologie*).



3. There is seasonal growth (mainly in late winter/early spring and in autumn) with intervening periods of moderate to low biomass. This pattern is mainly confined to spring-fed streams with few flood events (eg, Biggs and Close, 1989) and reflects the natural background dynamics of the communities in the absence of other physical forces. The reasons for this cycle are still unclear, but may relate to prolific spore development for some filamentous green algae at these times of year, perhaps initiated by certain light conditions. There may also be a link with seasonality in losses to invertebrates, whereby grazing activity is seasonally low because of reductions in water temperature, but temperatures are still sufficiently high for good periphyton growth.

An important implication of these three patterns in biomass dynamics is that it is difficult to arrive at any generalisations as to when peak biomass will occur in most New Zealand streams. Spring-fed streams are somewhat more predictable, but periphyton growth in all other types of streams and rivers tends to reflect local flow regimes. It is therefore important to have some knowledge (at least qualitative) of the normal annual hydrologic regime and biomass dynamics in any system under scrutiny before planning consent-oriented studies or resource investigations.

4.4 Spatial patterns

Small- to medium-scale (individual substrate particles to whole stream reaches) spatial patterns in periphyton communities can be best detected after prolonged periods of stable flow (eg, >6 weeks) and tend to reflect spatial variations in the stability of the substrates, spatial variations in water velocity and localised nutrient inputs (eg, groundwater upwellings). Broad-scale spatial patterns (among streams and regions) are best determined on the basis of monthly averages in community composition/biomass sampled over periods of a year or more.

4.4.1 Small scale: Substratum patterns

One of the most commonly observed spatial patterns in periphyton distribution is the association of biomass and community type with differences in the size of stream-bed particles (reflecting the average stability of the particles) (see also Section 3.3). In general, the larger, more stable the substratum the higher the biomass of periphyton. Thus, biomass on sand < gravels < cobbles < boulders < bed rock with the communities on the finer substrata being dominated more by unicellular diatoms and communities on the larger, more stable substrata being dominated by filamentous algae such as *Audouinella hermanii* and *Stigeoclonium* spp. (Biggs and Shand, 1987). Indeed, isolated boulders/bedrock can act as important refugia and may contain a much higher biomass than that found on unconsolidated sands/silts (up to 15 times) (Tett et al, 1978; Biggs and Shand, 1987).

However, exceptions to this also occur. For example, high biomass of some filamentous taxa such as *Vaucheria* can occur on silty banks (Figure 1), facilitated by the rhizoid attachment structures that this taxon has. Also, thick mats of the filamentous cyanobacterium *Phormidium* sp. can occur over silts in low-velocity areas late in summer low flows. Conversely, some parts of bedrock and boulders are heavily abraded by moving sands and gravels during flood events resulting in zones that are heavily scoured and generally clean of periphyton for much of the year (particularly just above the area of the bed level).

In many mountain streams, flat platey cobbles and some small boulders get deposited in very streamlined and stable configurations after large floods to form micro-form bed clusters (Biggs et al, 1997a). These resist small and moderate-sized floods and can accumulate a high biomass of periphyton (Francoeur et al, 1998).

A recent finding is that the surface texture of the substrata can have an important effect on the biomass of the communities (E.A. Bergey NIWA, pers. comm.). In general, the coarser the substratum the higher the biomass, reflecting greater availability of refuges and greater surface area for colonisation. In particular, pumice particles, with their high porosity and associated internal spaces/surfaces, can contain more than four times as much periphyton as greywacke stones of similar dimensions. In part, the differences relate to scale, whereby it is only feasible to estimate the "general" planar area of stones and not the full surface area of micro-scale undulations and crevices available for colonisation. Also, these crevices and undulations allow the cells to shelter from velocity forces and grazing with the result that more biomass can accumulate in these refugia. Thus, while the planar area and actual available area will be very similar for stones with smooth surfaces, they are quite different for stones with rough surfaces and pores. This has important implications for how periphyton are removed from stones for biomass estimation and evaluation of communities in relation to the recommended biomass criteria for protection of ecosystem values in streams (see technical manual).

4.4.2 Medium scale: Within reach and catchment patterns

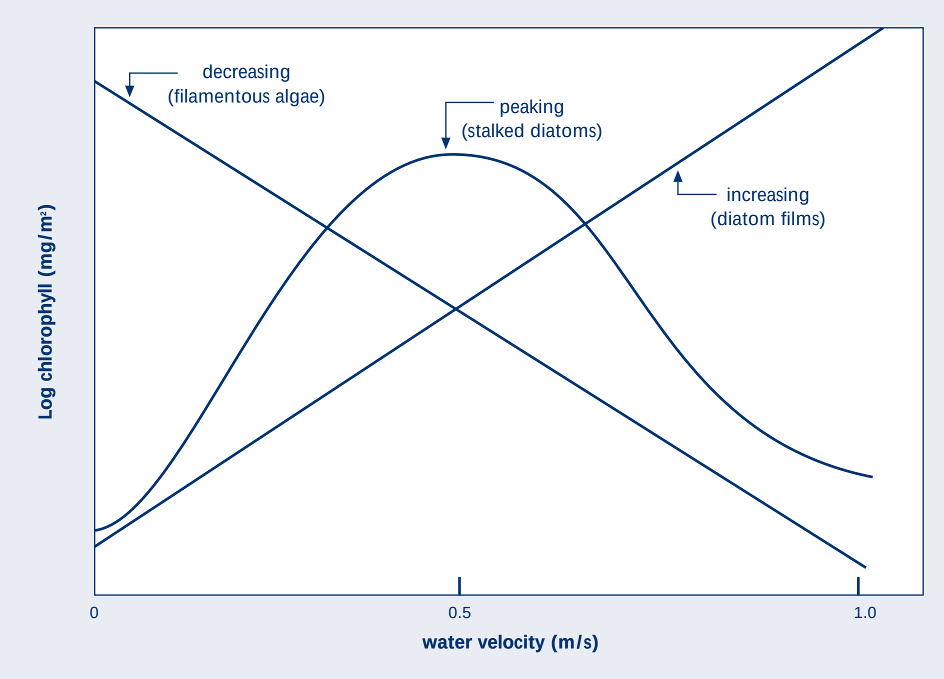
Differences in biomass and species among pools, riffles and runs are readily observable in most streams during prolonged periods of low flow. This represents the outcome of a combination of processes such as variations in bed substrate stability over the preceding months and variations in water velocity. The effects of water velocity can be particularly clearly seen in reaches with similar sized substrates such as cobbles.

Spatial variations in velocity control two important processes in stream periphyton. First, with higher velocities the thickness of the diffusive (laminar) boundary layer surrounding cells and filaments (and perhaps at the surface of some periphyton mats) is reduced which enhances mass transfer of metabolites to and from the mat with the result that metabolism and growth rates can be higher. Second, with such increases in velocity and higher biomass there is an increase in skin friction and form drag on the communities which tends to increase the rate of sloughing (Biggs, 1996b; Stevenson, 1996b). The result of these processes is expected to be quite complex.

Recently, Biggs et al (1998a) identified that the outcome of spatial variations in velocity on biomass could be quite different depending on periphyton community growth form. Three main responses were discovered. First, in some filamentous green algal communities (eg, *Oedogonium* spp., *Spirogyra* spp., *Zygnema* spp.) a loosely woven growth form enables high rates of mass transfer regardless of velocity. This means that highest biomass is often found at low velocities and any increase in velocity tends to result in major reductions in biomass because of the drag on the filaments (Figure 17). Second, with communities dominated by moderately loosely woven stalked diatoms and short filamentous taxa, maximum biomass occurs at medium velocities of around 0.5 m/s. Increases in mass transfer enhance biomass accrual at the low end of the velocity gradient, and after 0.5 m/s loss processes become progressively more important.

A third type of response is found in communities that form mucilaginous mats (eg, *Gomphoneis*). In these communities biomass continues to increase with increases in velocity within the normal 0–1.0 m/s range found in most streams (Figure 17). This is the community that most commonly dominates shallow, swift riffles in foothills-fed streams. The community is highly resistant to high velocities and seems to require such situations to form thick mats (Biggs and Hickey, 1994).

Figure 17: Three main community biomass responses to spatial variations in water velocity in streams.



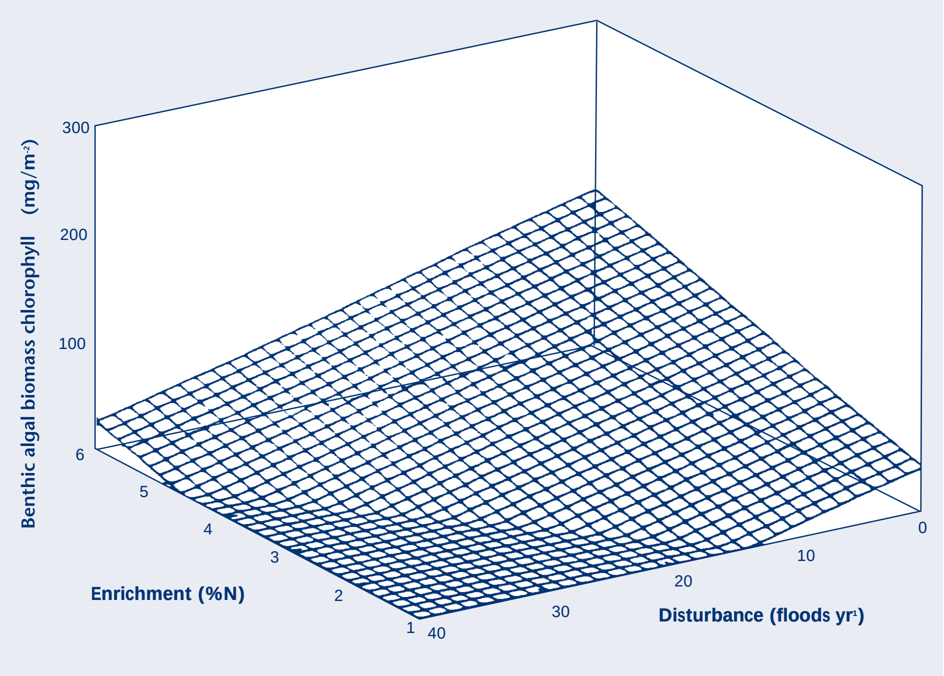
In some catchments there can be a progressive downstream increase in nutrient supply to streams/rivers associated with intensification of land use and the enrichment of seepage waters entering the streams. This usually results in a downstream increase in mean and peak low flow biomass in the streams (Biggs et al, 1998b). Often the valley gradient also decreases, resulting in a decrease in velocities and fining of the substrata. The reduction in velocities may allow a higher biomass of filamentous green algae to accumulate on areas of coarser substrate in these lowland reaches.

4.4.3 Broadscale: Intercatchment patterns

Major differences in the average biomass and growth form of periphyton clearly occur among different streams. During low flows, streams draining highly developed agricultural catchments tend to be dominated by high biomass, filamentous, communities. However, communities in streams draining forest catchments tend to be dominated by diatoms and cyanobacteria forming a low biomass (Biggs, 1990a, 1995). Because of the mosaic of different land uses, sometimes even among adjacent catchments, there are no general regional trends in periphyton community development in New Zealand (Biggs, 1990a; Biggs et al 1999). Communities most commonly reflect the state of local variations in flood frequency and enrichment (Biggs et al, 1998d).

A general representation of the joint effect of flood frequency and enrichment on mean monthly chlorophyll *a* biomass is depicted in Figure 18. The response surface used in the figure was generated empirically using data from 15 sites situated throughout New Zealand (multiple r^2 for chlorophyll $a = 0.87$). This shows that a high average biomass of periphyton occurs in streams where there is a combination of infrequent floods and high nutrients. Communities in such streams tend to be dominated by taxa that are architecturally complex, often with dense growths of filamentous green algae at certain times of the year (eg, summer). Conversely, communities tend to only form a low biomass dominated by architecturally simple, low growing diatom taxa, in streams that are subject to frequent flood events and/or low levels of enrichment. High enrichment can result in moderate periphyton biomass in streams that have a moderate frequency of flood events because of the rapid inter-flood regeneration. Some biomass can also accrue with low levels of enrichment providing flood frequency is also low (Biggs, 1995, 1996a).

Figure 18: Mean monthly periphyton chlorophyll *a* as a function of flood disturbance frequency and enrichment (as mat % N concentration) (reproduced from Biggs, 1995 with permission from *Freshwater Biology*).



5 The effects of human activities on variables controlling periphyton growth

Human activities in catchments and within the stream channel can have some profound effects on periphyton community development through their influence on the fundamental variables that control the growth and composition of mats (Table 4).

Table 4: Primary variables controlling periphyton community biomass accrual, general human activities that may influence these variables and the overall effects on periphyton biomass in shallow, stony streams.

Controlling variable	Human activity	Potential effects on biomass
Hydrological disturbance	flow regulation (reducing flow variability and increasing bed stability)	increase
	flow regulation (increasing flow variability)	decrease, but depends on pre-regulation conditions
	gravel abstraction (bed destabilisation)	decrease, particularly if gravel removal is from within the wetted channel
	intensification of land use, forest/scrub removal (increased runoff and bed destabilisation)	decrease, particularly if catchment is steep
Nutrient supply	wastewater discharges (increased nutrient supply)	increase, particularly if from effluent ponds/treatment systems into shallow, stony bedded oligotrophic and mesotrophic streams
	intensification of land use, forest/scrub removal (increased nutrient supply)	increase, providing it is not accompanied with excessive siltation
Light supply	riparian vegetation removal (increased light)	increase, in 1st- to 3rd-order streams
	intensification of land use, forest/scrub removal (increased suspended sediment)	decrease, through increased siltation
Invertebrate grazing	intensification of land use, forest/scrub removal (increased siltation)	increase, if siltation of invertebrate interstitial habitat decreases grazing activity
Baseflow velocity	abstraction/diversion (decreasing velocities)	increase, if filamentous green algae; increase or decrease, if stalked diatom/short filamentous communities; decrease, if mucilaginous communities
Baseflow temperature	abstraction/diversion (increased temperature)	increase, particularly if there is no riparian shade

5.1 Hydrological disturbance

In general, it is difficult to influence the hydrological disturbance regime of streams and rivers because of the high magnitude of flows during floods. However, in New Zealand a number of medium to large rivers have their flows largely stopped or diverted into holding reservoirs during summer for activities such as irrigation and winter power generation. This has three consequences for periphyton communities. First, the placing of a dam or some form of barrage across the river alters (or completely stops) the flow of bed sediments moving down the river. This then usually enhances bed armouring (ie, paved with very stable, large cobbles and boulders on the surface layers; see Figure 19) which provides excellent substrata for periphyton to attain a high biomass. Second, most of the small- and medium-sized floods are prevented from flowing down the river (unless the reservoir is at storage capacity), which means that the normal flow variability is reduced and the natural ability of the system to remove excess accumulations of biomass is also reduced. Third, the reduction in flow usually also results in a reduction in water velocities, which then allows a higher biomass of filamentous green algae to develop if nutrient levels are sufficient.

A fourth factor, related to nutrient supply regimes, may also be important in some rivers. Significant groundwater intrusion can occur into the residual channel (probably partly enhanced by the greater hydraulic head with the upstream impoundment). This groundwater is usually more enriched than the river and can therefore have a stimulatory effect on biomass accrual. Thus, a common feature of regulated, residual flows throughout the world is periodic proliferations of periphyton (Lowe, 1979; Biggs, 1987, 1996b).

Figure 19: Armoured residual channel of the Tekapo River below the Lake Tekapo control gates during summer. Note the dominance of large cobbles and boulders on the surface layer.

Conversely, in rare situations flows are stored for short periods (eg, overnight) and much higher discharges (approximately double) are released during the day. This creates a more variable flow regime with the potential to be quite destructive on downstream periphyton communities. However, in reality the effects may be countered by increased bed stability. Indeed, if the slope of the bed is low then the doubling of discharge may only have a minor (say <20 percent) increase in near-bed velocities (eg, Lower Clutha River).

It is possible that an intermediate frequency of flood disturbance events is good for the diversity of benthic communities in streams (Townsend et al, 1997). From this, and other research, we have a general idea of what the appropriate frequency of flood events should be in natural rivers to maintain a diverse benthic community (including preventing periphyton proliferations) (Clausen and Biggs, 1997; Townsend et al, 1997). For example, Rutledge et al (1992) reported data which suggested that proliferations of periphyton could occur in experimental channels in the oligotrophic Waitaki River when there were <13 floods/year (of greater than three times the existing flow), but proliferations did not occur when there were >26 floods/year. Biggs and Close (1989) also carried out an analysis of the effects of different intensity flushing events on suspended algal concentrations (mainly derived from the bed periphyton) in the Hawea River, Otago. They found that an eight-fold increase in flow was necessary to obtain a major increase in periphyton sloughing. However, it would be valuable to carry out further field experiments on the effects of different flow variability in regulated rivers because flushing is potentially a useful mechanism to control proliferations of periphyton in such rivers.

Other activities related to hydrological disturbance that could significantly effect periphyton communities include gravel abstraction and intensification of land use. Excavating large amounts of the bed as a source of gravel can break up the surface fabric of the channel and render it more prone to moving during small and medium-sized floods. This can be locally destructive in streams that are not usually prone to flooding. However, this has never been determined with specific studies, and our ability to manage such enterprises would greatly benefit from long-term-impact studies of these activities. Conversely, in flood-prone rivers that carry large amounts of bed sediments the effects are likely to be minor in comparison with natural processes (eg, some of the large South Island glacier-fed braided rivers).

Intensification of land use can result in increased bank destabilisation and in increased suspended and bedload sediment inputs, which will abrade periphyton communities and destabilise substrata. Large amounts of silt and debris often occur with excavation of new roads in steep hill country unless appropriate measures are taken to immediately stabilise banks and cuttings. Increases in the silt and sand fraction transported during high flows can result in increased abrasion of periphyton communities (particularly the thinner film diatom communities). Recent experiments have been carried out to investigate the relationship between suspended solids concentrations and biomass loss (Heinlein and Biggs, unpublished data). However, experiments need to be carried out with a range of periphyton community types to determine whether community specific limits in suspended solids need to be set.

Conversion of scrub/forest to pasture or hard urban surfaces also increases runoff rate and the magnitude of flood events which can be harsh on periphyton communities in streams not normally prone to such disturbances. Where the frequency of intense events increases it is likely that significant effects will occur on the periphyton. However, it will be difficult to separate these from other components of land use change such as increased sediment loads. If the frequency of intense events (eg, greater than seven times the medium flow) increases much beyond about 15/year, then a low average periphyton biomass can be expected (Biggs, 1995; Clausen and Biggs, 1997).

5.2 Nutrient supply

Enhanced periphyton biomass through nutrient enrichment usually occurs as a result of one or other of two human activities: point-source discharges of wastes and intensification of land use. Most wastes receive primary and secondary treatment before being discharged to open water courses. Thus, the low molecular weight organics that could stimulate sewage fungus growth are generally removed along with large quantities of organic phosphorus and nitrogen. However, depending on the receiving environment, there may be sufficient residual inorganic nitrogen and phosphorus in the effluent to enhance peak biomass at certain times of the year. Of all the human activities potentially affecting stream periphyton growth, and perhaps initiating proliferations, point-source nutrient enrichment is probably the easiest to control.

Less easy to control, and most prevalent in New Zealand, are the enriching effects of land development (Cooper and Thomsen, 1988; Close and Davies-Colley, 1990; Smith et al, 1993; Quinn et al, 1997a). However, it also needs to be clearly understood that a large degree of natural enrichment occurs through leachate from nutrient-rich rocks such as andestic volcanics, Tertiary marine mudstones/sandstone, and limestone (Close and Davies-Colley, 1990; Biggs and Gerbeaux, 1993; Biggs, 1995). Indeed only small amounts of these rock types in a catchment can cause proliferations during low flows (Figure 20). Enriching effects from agricultural development can start to become evident with as little as 20 percent of the catchment converted to intensive pasture and maximum effects can occur when greater than 40 percent is converted (Biggs, 1995). This non-linearity of effect is partly because of the high sensitivity of periphyton communities to even slight increases in nutrient loading. Thus even minor losses of nutrients from pasture lands and topdressing can represent large increases in the supply rates of nutrients to periphyton which normally receive nutrients at extremely low (parts per billion) levels. In general, no simple rule is likely to exist for defining the extent of a catchment that can be converted to agriculture before significant enrichment of the stream occurs. This is because the degree of nutrient loss to streams depends on many different factors such as soil type, whether irrigation is used, the relief of the land, the exact intensity and type of development, the extent of shallow groundwater intrusion into the streams, the extent of riparian vegetation, climatic zones etc.

Figure 20: Proliferations of *Cladophora* in the Waipara River, North Canterbury downstream of seepage zones draining Tertiary marine sediments.

In many situations such as where streams flow over alluvial plains, major inputs of enriched groundwater are the principal source of enrichment (Figure 6). The higher nutrient concentrations may well come from any upstream farming activities, but most of these activities will be a long way from the stream channel. Worst-case scenarios are easily identified, such as where a farmer allows open stock access to channels on grazing land (Figure 21).

However, there are other situations where streams flow through intensively developed dairy farms and yet high water quality is still maintained in the streams. This is achieved because the streams are derived from high flowing artesian springs, they have good riparian vegetation, and good supplies of stock water are provided on the paddocks.

Figure 21: Two contrasting treatments of stream environments in agricultural lands. The upper photo illustrates the destruction of habitat in first-order tributaries and how streams draining such areas can become silted and enriched. These small streams coalesce to form the bigger streams and rivers so are the first place to start with habitat protection measures. The lower photo illustrates good farming practice with the preservation of vegetation cover around a first-order stream.

5.3 Light

Destruction of riparian vegetation usually accompanies an intensification of land use. While potentially reducing the supply of nutrients and silt to the stream and stabilising banks, one of the major benefits of maintaining an adequate riparian cover along streams is to reduce light intensity to the stream bed. However, major reductions in light intensity (eg, >60 percent) appear to be required to reduce the incidence of proliferations (Quinn et al, 1997b; S. Rier and R.J. Stevenson, pers. comm.) because periphyton can acclimate to moderately low light levels by increasing the concentrations of chlorophyll in their cells.

In small streams, heavy shading does have the potential to prevent proliferations of green filamentous algae and the effects of removing this cover on periphyton growth has been widely documented (Lowe et al, 1986). Careful management is required for the riparian zone to regenerate properly. Usually, some supplementary planting is required (see Collier et al (1995) for more information). Many farmers are reluctant to exclude stock from these zones because the areas then become a major source of weeds until over-storey vegetation has become established.

Intensification of land use, forestry and activities such as alluvial gold mining in stream beds can also increase the suspended sediment load to streams. This occurs both through overland flow, destabilisation of the stream banks and direct disturbance of the streambed. Increased silt loads can reduce the amount of light penetrating to the stream bed which, in general, can be expected to reduce the photosynthetic activity and biomass of periphyton (Davies-Colley et al, 1992). However, a more significant effect of increased silt loads can occur through invertebrate communities. While many periphyton taxa (eg, *Gomphoneis* and *Ulothrix zonata*) appear reasonably silt tolerant (Biggs and Price, 1987), siltation of the substrate reduces the quality of periphyton as food for many benthic invertebrate grazers (Graham, 1988; Quinn et al, 1992). A reduction in grazing pressure may, to some extent, compensate for shading effects on the periphyton.

5.4 Baseflow velocity

A reduction in baseflow velocity associated with abstraction or diversion of flow, particularly if accompanied by increased enrichment, has the potential to greatly enhance the peak biomass of filamentous green algae in enriched gravel/cobble bed streams (Biggs et al, 1998a, d). As noted above, this commonly occurs in impoundment regulated rivers, but is also commonly observed in normally free-flowing rivers. Velocities become reduced below a level where sloughing can counteract biomass accrual and large mats may accumulate (particularly in association with enrichment). It should be noted, however, that no data are available from streams above and below abstraction points to specifically quantify the effects of abstractions on periphyton accrual. Such information could provide valuable insights into the management of low flows in rivers.

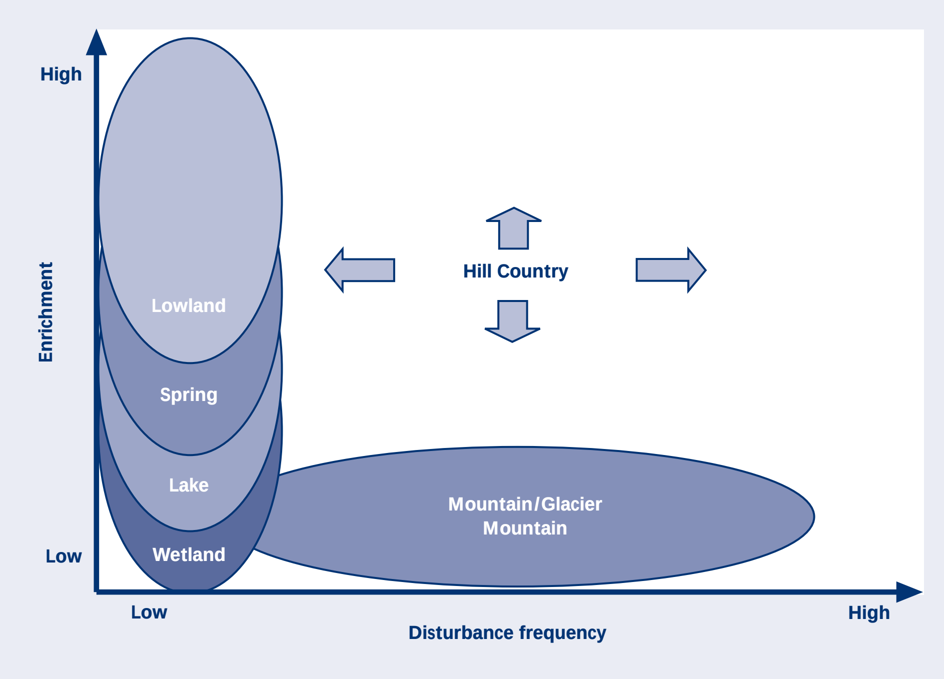
5.5 Baseflow temperature

Abstraction and diversion of flows during summer has the potential to cause increases in water temperature. In part this is accentuated by the fact that the residual flow tends to be very shallow (ie, flows spread out over the remnants of the river channel) and partly because the water velocities are greatly reduced. In most larger streams and rivers there is also no riparian shade because of the width of the natural channel. The effect of this is likely to be that periphyton growth rates are increased. We have little knowledge of the temperature sensitivity of common periphyton taxa, but it is known that some invertebrates are sensitive to high temperatures (ie, Quinn et al, 1994). Indeed, Quinn and Hickey (1990) found that stoneflies were largely absent in streams with summer temperatures typically greater than 19°C. Such restrictions on invertebrate distributions could have a cascading effect on periphyton by reducing grazing pressure.

6 Periphyton communities in New Zealand streams

As discussed earlier, the development of periphyton in streams is the product of a hierarchy of physical variables that interact to provide the habitat for the community. The most significant variables can be summarised as those promoting growth (limiting resource supply, usually nutrients) and those promoting loss (most commonly by flooding, but also invertebrate grazing). Different combinations of these variables occur in nature to create a "habitat matrix" (Figure 22). The different cells in this matrix encompass characteristics that are found in specific stream types, or parts of streams. Different populations (and the resultant communities) have evolved to exploit these habitats.

Figure 22: Location of common New Zealand stream and river types on a habitat matrix defined by gradients in flood disturbance frequency and nutrient enrichment.



There is potentially great benefit in specifically classifying stream habitats in such a way and then defining the periphyton communities that normally inhabit such areas. This should then enable the variability in stream environments and biota to be stratified so as to provide a clearer understanding of factors controlling community development and assisting in their management (Biggs et al, 1990; Hughes et al, 1994; Rutherford, 1996; Snelder et al, 1998).

This chapter describes the most commonly found taxa comprising periphyton communities in New Zealand streams, including a summary of the trophic status of habitats where these communities would normally be expected. The biomass characteristics of these communities are also reviewed.

6.1 Common periphyton communities in New Zealand streams

The majority of common stream periphyton taxa in New Zealand occur widely elsewhere in the world. We can therefore utilise a wealth of taxonomic guides developed in Europe and North America (indeed, about 26,000 algal taxa have already been recognised and described from elsewhere in the world (Stevenson, 1996a)). There is also a steadily developing body of information on the habitat requirements and pollution tolerances of the taxa that can be used to assist with assessing water quality conditions or predicting the potential effects of planned changes to water or catchment management regimes.

The most common periphyton in New Zealand streams are members of the diatoms, followed by green algae and cyanobacteria (Biggs and Price, 1987; Biggs, 1990a). Red algae are much less common and generally restricted to boulder or bedrock habitats. Extensive nationwide sampling has identified a "core" group of 33 taxa in New Zealand streams and rivers (Table 5). It can be considered "core" because in a very large proportion of our streams members of this group will usually comprise greater than 70 percent of the biomass.

Table 5: Summary of the "core" periphyton taxa of New Zealand streams and rivers (derived from Biggs and Price, 1987; Biggs, 1990a) (*, denotes taxa forming macroscopically distinctive communities which can be identified in the field when developed as a thick mat).

Division	Taxa
Bacillariophyta (diatoms)	*Achnanthidium minutissimum* *Cocconeis placentula* *Cymbella kappii** *Cymbella minuta* *Diatoma hiemale* var. *mesodon** *Epithemia sorex* *Fragilaria vaucheriae* *Gomphoneis minuta* var. *cassieae** *Gomphonema parvulum* *Melosira varians** *Navicula avenacea* *Navicula cryptocephala* *Navicula rhyncocephala* *Nitzschia* sp. *(v. small)* *Nitzschia palea* *Rhoicosphenia curvata* *Synedra rumpens* *Synedra ulna*
Chlorophyta (green algae)	*Bulbochaetae* sp. *Cladophora* sp. *Cladophora glomerata** *Microspora* sp.* *Oedogonium* spp.* *Rhizoclonium* sp.* *Spirogyra* spp.* *Stigeoclonium lubricum** *Ulothrix zonata**
Chrysophyta (chrysophytes)	*Vaucheria* sp.*
Cyanobacteria ('blue-green algae')	*Calothrix* sp. *Lyngbya* sp. *Nostoc* sp.* *Phormidium* sp.* *Schizothrix* sp.
Rhodophyta ('red-algae')	*Audouinella hermanii** *Batrachospermum* sp.* *Compsopogon coeruleus**

Many of the taxa listed in Table 5 combine in different ways to form seventeen main periphyton community types in New Zealand streams and rivers (Biggs and Shand, 1987; Biggs and Price, 1987; Biggs, 1990a,1995; Biggs et al, 1998b; S. Moore pers. comm.). It is convenient, and helps with interpretation, to subdivide the list into groups normally associated with oligotrophic, mesotrophic and eutrophic habitats (Table 6). Details on community biomass and general habitat features are given in the technical manual.

Table 6: Periphyton communities commonly found in New Zealand streams and rivers of different trophic state.

Community identification code and primary taxon/taxa	Secondary filamentous taxon/taxa	Understorey taxa
Oligotrophic habitats		
O1: *Audouinella hermanii*	Rare	*Cymbella kappii, Synedra ulna, Fragilaria vaucheriae*
O2: *Lyngbya* sp.	Rare	*Synedra ulna, Gomphoneis minuta var. cassieae, Navicula avenacea*
O3: *Schizothrix/ Calothrix/Lyngbya*	Rare	
O4: *Ulothrix zonata*	*Microspora* sp., *Spirogyra* spp., *Oedogonium* spp.	*Synedra ulna, Cymbella kappii, Gomphoneis minuta var. cassieae, Gomphonema parvulum, Fragilaria* sp.
O5: *Nostoc* sp.	*Microspora* sp., *Gomphoneis minuta var. cassieae*[1], *Phormidium* spp., *Audouinella hermanii*	*Navicula* spp., *Synedra* spp.
Mesotrophic habitats		
M1: *Cladophora* sp.	*Oedogonium* spp., *Melosira varians*	*Gomphonema parvulum, Cymbella kappii, Synedar ulna, Cocconeis placentula, Navicula rhyncocephala*
M2: Fragilaria/Gomphonema *tenellum/Synedra ulna/ Synedra rumpens/ Cymbella minuta/ Gomphoneis minuta* var. *cassieae*	Rarely *Ulothrix zonata, Stigeoclonium lubricum*	
M3: *Gomphoneis minuta* var. *cassieae/Cymbella kappii*	*Ulothrix zonata, Stigeoclonium lubricum*	*Cymbella kappii, C. minuta, Synedra ulna, Fragilaria vaucheriae*

Community identification code and primary taxon/taxa	Secondary filamentous taxon/taxa	Understorey taxa
M4: *Oedogonium/ Microspora/ Zygnema*	*Spirogyra* spp., *Melosira varians, Microspora* sp.	*Synedra ulna, Cocconeis placentula, Navicula rhyncocephala*
M5: *Phormidium* spp.	Rare	*Synedra ulna, Cymbella kappii, Gomphoneis minuta* var. *cassieae, Cocconeis placentula, Gomphonema parvulum, Cymbella minuta*
M6: *Spirogyra* spp.	Rarely *Oedogonium* spp., *Cladophora* sp., *Phormidium* spp., *Stigeoclonium lubricum*	Rarely *Gomphoneis minuta* var. *cassieae, Synedra ulna, Cymbella kappii, Gomphonema parvulum, Achnanthidium lanceolatum, Cocconeis placentula*
M7: *Stigeoclonium lubricum*	Rare	*Gomphonema parvulum, Gomphoneis minuta* var. *cassieae, Cymbella kappii, Synedra ulna*
M8: *Vaucheria* sp.	Rare	*Rarely Navicula spp., Cymbella spp., Synedra* spp.
Eutrophic habitats		
E1: *Melosira varians*	*Oedogonium* spp.	*Synedra ulna, Cocconeis placentula, Navicula cryptocephala, Navicula rhyncocephala*
E2: *Cladophora glomerata*	*Rhizoclonium* spp.	*Epithemia sorex, Cocconeis placentula, Synedra ulna, Cymbella kappii, Gomphoneis minuta* var. *cassieae*
E3: *Rhizoclonium* sp.	*Cladophora glomerata, Melosira varians*	*Cocconeis placentula, Synedra ulna, Cymbella kappii, Navicula avenacea, Rhoicosphenia curvata, Nitzschia* spp.
E4: *Sphaerotilus natans, Zoogloea* sp., *Stigeoclonium tenue*	*Melosira varians, Phormidium* spp.	*Cocconeis placentula, Cymbella* spp., *Fragilaria* spp., *Gomphonema parvulum, Nitzschia palea*

Note: [1]Gomphoneis minuta var. cassieae was previously known as G. herculeana

Differences in community structure as a function of enrichment tend to be more clear cut at the extremes (eg, oligotrophic vs. eutrophic). It also needs to be recognised that the communities defined here may not be all the possible types for these habitats because of some locally important, overriding, variable.

Oligotrophic taxa are often found as a common component of communities in mesotrophic habitats (they can also extend into eutrophic habitats), and mesotrophic taxa can be common in eutrophic habitats. Also, diatoms that are normally only competitive in oligotrophic or mesotrophic habitats may dominate eutrophic habitats for weeks after disturbances, or for much longer periods if disturbances are frequent (Biggs et al, 1998d). However, apart from some ubiquitous diatom taxa such as *Gomphoneis minuta* var. *cassieae* the reverse very rarely occurs, (i.e., eutrophic taxa being abundant in oligotrophic habitats).

The oligotrophic climax communities (Table 6) include members of three of the four main Divisions of algae. Very long periods without floods are generally needed for communities to reach climax or peak biomass community at oligotrophic sites. This is because growth rates are so slow. In mountain and hill-country streams, the bed is often initially colonised by diatoms such as *Gomphoneis*, *Synedra* and *Cymbella* soon after a flood, and these taxa then monopolise substrata for considerable periods (Biggs et al, 1998b). The oligotrophic communities tend to dominate streams draining forest catchments underlain by nutrient poor metamorphic rocks and/or granites. Peak biomass of these communities tends to be moderate to low.

The mesotrophic climax communities (Table 6) include members of four algal Divisions. Communities dominated by *Cladophora*, *Phormidium* and *Stigeoclonium* tend to be slow to colonise and /or to have slow growth rates, thus needing prolonged periods without flood disturbances before dominating a mesotrophic site. *Phormidium* forms particularly conspicuous dark brown or black patches over individual cobbles (Figure 23) or over sand/silts in peripheral areas late in the successional sequence (most commonly in late summer in foothills rivers). Only rarely does *Phormidium* cover enough of the stream bed to fully dominate a site.

Figure 23: Dark skein of interwoven *Phormidium* filaments over thick mucilage on a cobble.

The diatom-dominated communities (*Fragilaria* and *Gomphoneis*/*Cymbella*, Table 6) are early colonisers following flood disturbances (they may also be more resistant to removal by floods) and often monopolise sites in upland/foothills rivers for very long periods (particularly in the South Island). The *Gomphoneis*/*Cymbella* community forms thick mucilage slimes and is stimulated by higher water velocities.

The *Spirogyra*-dominated communities (Table 6) are generally not well attached and thus are not commonly found in swifter gravel/cobble bed streams. This community tends to proliferate most in low velocity areas on the periphery of channels and can form conspicuous dark green clouds in pools or backwaters of some streams (Figure 24). Very few other taxa tend to be associated with *Spirogyra* when it dominates in slow velocity areas.

Figure 24: Clouds of *Spirogyra* in a spring-fed pool near the Hawdon River, Arthurs Pass National Park.

Vaucheria also tends to form fairly monospecific mats and is most prominent on silty/sand substrates. This community will only rarely be found dominating communities in the middle of gravel/cobble bed rivers. *Vaucheria* is tolerant of cold waters and can often be found forming extensive beds on silts in spring-fed streams (Figure 1).

The eutrophic climax taxa (Table 6) tend to be more summer dominants and form extensive green mats in enriched streams during low flows, though they can occur in oligo-mesotrophic waters (eg, Upper Waikato River). *Cladophora glomerata* is one of the most common taxa in the world and is usually associated with eutrophic streams (Dodds and Gudder, 1992). It is also the most likely taxon to form proliferations and degrade habitats. However, *Cladophora* tends to require warm waters (ie, >15°C) and high calcium concentrations to proliferate so is most common in enriched North Island streams draining limestone and marine Tertiary siltstone/mudstone catchments. In cooler South Island enriched streams, these communities tend to be replaced *Microspora*, *Oedogonium* and *Vaucheria*.

Cladophora and *Rhizoclonium* communities (Table 6) are a light to dark green when they initially develop, but late in the season can become quite brown and slimy as the filaments become heavily colonised with epiphytes (mainly diatoms). *Rhizoclonium* is often found as a component of *Cladophora glomerata* mats and only occasionally dominates the communities in eutrophic streams in New Zealand. Parts of these mats are continually sloughing from the bed and often attached to downstream projections from where they continue to grow forming extensive filamentous streamers (Figure 3). *Melosira varians* is very fragile and tends to grow more from a basal chain entangled in other parts of the mat. Thus, significant growths of this community tend to be restricted to low velocity habitats where they can form brown clouds of filaments.

6.2 Unusual/unique/rare or endangered taxa or communities in New Zealand streams

Although the majority of taxa in our communities are cosmopolitan, our knowledge of the taxonomic composition and distribution of stream periphyton is still far from complete and we are unable to identify unique or rare taxa/communities at present. For example, in 1987 Biggs and Price reported the first recording in New Zealand of the branched filamentous red alga *Audouinella hermanii* from six streams/rivers, and its occurrence was initially thought to be rare and significant. However, at one of those sites (Lower Clutha River below the Roxburgh hydroelectric dam), a more extensive survey during very low flows subsequently revealed that *Audouinella* was the dominant taxa covering most of the bedrock (Biggs and Shand, 1987). Then further collecting identified *Audouinella* as one of our most common taxa in cobble-boulder bed headwater streams (Biggs, 1990a; Biggs unpublished data).

Recent collecting and taxonomic research has identified a number of new species (and possibly genera) from some pristine and more remote habitats (R.L. Lowe and C. Kilroy pers. comm.). These taxa have been diatoms and have constituted a large proportion of the communities in the streams where they were found. It is likely that with more extensive surveys of some of our remote regions and unusual/extreme habitats, many new or rare populations or communities will be found. An additional finding of this work has been extensive mats of the large, branched, filamentous red alga *Batrachospermum* in stable Westland streams. This taxa was also thought to be rare in New Zealand, but is probably quite widespread in streams with stable beds and high soluble organic carbon in the waters.

6.3 Biomass

Once the general type and physical structure of a periphyton community has been identified, the next most important aspect is determining community biomass. Biomass is the quantity of organic matter (or carbon) that has accumulated from the periphyton production per unit area of stream bed. The two most common, and easily used, methods for estimating this biomass are ash-free dry mass (AFDM) and chlorophyll *a*. However, it is often not recognised that these variables are measuring two different attributes of the community. Often they will be very highly correlated, but there are a few important situations where they will not agree.

6.3.1 Ash-free dry mass

AFDM is determined as the difference in weight between the dried sample and sample after all the organic matter has been burnt off. It thus measures the total quantity of combustible products in the mat (alternatively this variable is often called loss-on-ignition). The ignited material is generally assumed to be carbon, but of course includes all other protoplasmic material within the cells, and external mucilages. While it is reasonably easy and quick to determine, the interpretation of AFDM has two major problems. Firstly, because of the errors involved in drying, ashing and weighing in relation to the generally small amount of material analysed, the method is insensitive to low levels of biomass. Secondly, periphyton communities tend to accumulate debris from upstream mats and terrestrial vegetation. This is a significant problem in forest streams and those draining wetlands. Unless this debris can be clearly identified and removed from the sample, it will create error in the estimates of amounts of periphyton.

Dry matter is often used in other branches of ecology to quantify plant and/or animal biomass. This is just the dried weight of material without an additional ashing step to the analysis. However, the dry weight analysis does not separate organic matter from accumulated silt and sand debris in the mat. In some samples this debris may be many fold larger that the quantity of organic matter. Thus, the use of dry matter is discouraged for quantification of stream periphyton biomass.

A detailed protocol for determining AFDM in periphyton samples is given in the technical manual accompanying this *Guideline*.

6.3.2 Chlorophyll *a*

Chlorophyll *a* is a pigment present in large quantities in most algae to enable photosynthesis. Chlorophyll is extracted from periphyton samples using an organic solvent (usually ethanol or acetone), and the concentration of chlorophyll is then measured in a spectrophotometer. This gives a relative measure of autotrophic biomass. The advantages of this method is that it is quicker than AFDM, it is not biased by non-periphytic organic matter, and it is several orders of magnitude more sensitive to low biomass levels. This method has therefore become the most widely used means of estimating stream periphyton biomass. However, it also has some draw-backs.

The most important of these is that the chlorophyll *a*:carbon ratio varies within a given species depending on how much light there is (ie, chromatic adaptation), it varies greatly among different Divisions of algae, and it varies depending on the degree of nutrient limitation. This means that for a given quantity of carbon, the quantity of chlorophyll *a* could vary two- to threefold. It is virtually impossible to compensate for all these problems, because generally we don't know the exact effect. Obvious problems can be avoided in comparative studies, such as standardising light conditions among sites when sampling. Usually, it is assumed that variation in chlorophyll *a*:carbon ratio among sites as a result of differences in taxonomic structure of the assemblage is much smaller than differences associated with environmental perturbations.

Notwithstanding the above cautions, in some instances it might be useful to be able to approximate one measure of biomass from another. Regression equations between chlorophyll *a* and AFDM derived from analyses on 170 samples collected from a wide range of periphyton communities (and biomass) throughout New Zealand have been developed and are as follows:

$$\text{Ln Chlorophyll } a \text{ (mg/m}^2\text{)} = 0.338 + 1.396 \text{ X Ln AFDM (g/m}^2\text{)}$$
$(r^2 = 0.790, N = 170)$

$$\text{Ln AFDM (g/m}^2\text{)} = 0.186 + 0.566 \text{ X Ln chlorophyll } a \text{ (mg/m}^2\text{)}$$
$(r^2 = 0.790, N = 170)$

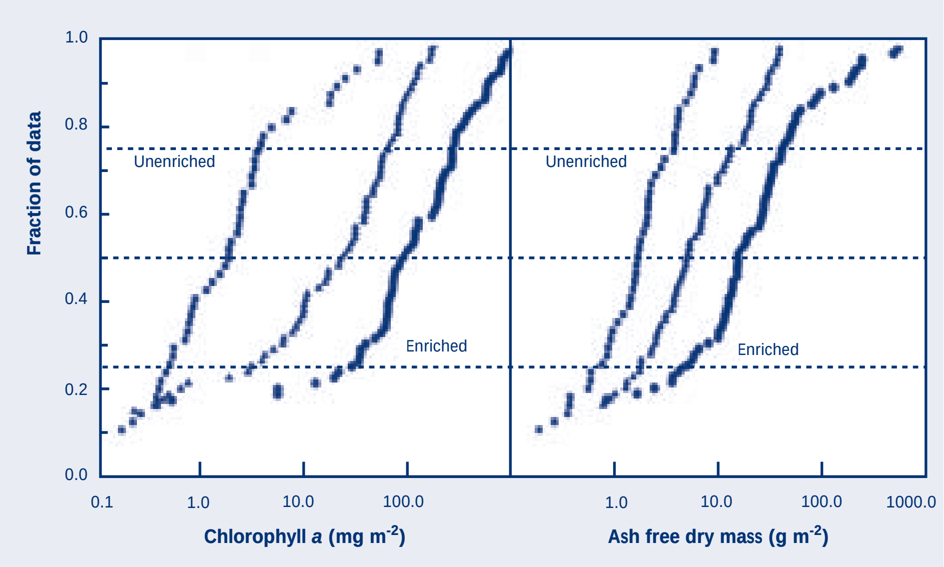
A detailed protocol for determining chlorophyll *a* in periphyton samples is given in the technical manual.

6.4 General biomass characteristics of periphyton communities in New Zealand streams

Extensive research on periphyton over annual cycles in a large number of New Zealand streams and rivers has given us a good understanding of biomass characteristics in New Zealand waterways. It is clear that there is extremely high variability among streams (and over the year) induced by differences in degree of nutrient enrichment and frequency of flood events. However, it is useful to separate streams and/or sites according to the degree of enrichment because enrichment has a major bearing on inter-flood regeneration rates, peak biomass during hydrologically stable periods, and thus the overall statistical distribution of biomass values.

Figure 25 displays cumulative frequency curves for chlorophyll *a* and AFDM from 16 New Zealand streams sampled monthly for a year. The data are separated in unenriched/oligotrophic (four streams), moderately enriched/mesotrophic (six streams) and enriched/eutrophic (six streams), based on catchment geology, land use and water quality variables (see Biggs, 1995). Overall, 75 percent of the chlorophyll *a* concentrations were <80 mg/m^2 and 75 percent of AFDM values were <10.8 g/m^2, with the median for all the data being 20 mg/m^2 chlorophyll *a* and 5 g/m^2 for AFDM. For oligotrophic streams (forested catchments on hard metamorphic rocks) the upper and lower quartiles define that chlorophyll *a* was typically in the range of 0.5–3.0 mg/m^2 (median of 1.7 mg/m^2). For mesotrophic streams (catchments that were moderately developed for agriculture), chlorophyll *a* was typically in the range of 3–60 mg/m^2, with a median of 21 mg/m^2. For eutrophic streams with catchments that were highly developed for agriculture and/or underlain by nutrient-rich rocks, chlorophyll *a* was typically in the range of 25–260 mg/m^2 with a median of 84 mg/m^2. High chlorophyll values (ie, >100 mg/m^2) occurred for approximately 40 percent of the year in these eutrophic streams, which compares with <1 percent of the year in the mesotrophic streams (Biggs, 1996a).

Figure 25: Cumulative frequency curves for chlorophyll *a* and ash-free dry mass from unenriched/oligotrophic sites (squares), moderately enriched/mesotrophic sites (triangles), and enriched/eutrophic sites (dots) in New Zealand streams sampled every 4 weeks for a year (data pooled for groups of sites in each enrichment category with N = 4, 6, and 6 sites respectively; see Biggs, 1995 for sampling and site information). The dashed lines denote the 25th, 50th and 75th percentiles (reproduced from Biggs, 1996a with permission from Academic Press).



7 Periphyton as environmental indicators

7.1 Introduction

Periphyton have long been a primary tool for measuring the degree of enrichment and pollution of waterways in Europe (see, for example, the saprobic system of Kolkwitz and Marsson, 1908, 1909). Since the mid-1960s, this community has also become widely used in North America as a water quality indicator (Palmer, 1969; Patrick, 1973). There has, however, been a long debate as to whether it is, or is not, better to use chemical parameters, and then – if it is agreed that biological sampling/ monitoring should be carried out – whether or not periphyton, invertebrates or fish should be used as the primary indicator of interest.

While periphyton/algae give some very useful and unique information (some enthusiasts have said that "diatoms represent *outstanding* bioindicators for different degrees of pollution" Lange-Bertalot, 1979) such debates are largely academic, compared with the real world of water resource management. All these methods and communities give somewhat complementary information.

Many criteria have been suggested for selecting appropriate biological measures of environmental change. In a synthesis of views, Cairns et al (1993) proposed a generic list of 16 attributes for biological indicators. The six most important of these are:

1. biologically relevant (ie, easily related to the maintenance of ecosystem integrity)
2. socially relevant (ie, of obvious value to those involved in the decision-making process, including the general public)
3. broadly applicable to many stressors and sites
4. sensitive to stressors, preferably without an all-or-nothing response and without excessive natural variability
5. measurable, operationally definable and quantifiable by using an accepted procedure with known precision and accuracy
6. interpretable (ie, capable of distinguishing acceptable from unacceptable conditions in a scientifically and legally defensible manner).

It is unlikely that any one indicator would possess all necessary attributes. However, stream periphyton satisfy many. In particular, taxa in the periphyton community are ubiquitous and ecologically important, they are sensitive to a broad range of stressors, they can provide information not provided by animals, they respond rapidly to change, benchmark/reference conditions are easily defined, and they are cost effective (McCormick and Cairns, 1994).

The question then arises: what general approach should be taken in using periphyton to evaluate environmental conditions and what parameters should be used? The following principles should be considered:

First, use synoptic surveys, or routine monitoring, of a "basket" of biological communities in streams to identify any potential problems and/or long-term state of the environment monitoring. The communities themselves are the ultimate, integrative, measure of the health of a waterway and the focus of the RMA. Different communities will be more sensitive to certain types of pollution or change in water resources use than others. For example, periphyton growth rate will be a more sensitive and relevant indicator of nitrogen and phosphorus enrichment than invertebrate community diversity or an invertebrate pollution index, but invertebrates will be a more sensitive indicator of oxygen depletion or temperature problems.

Second, if a potential problem is isolated, design a comprehensive investigation that involves analysis of the most relevant water quality parameters and biological communities. If the potential problem involves inorganic nutrients and low flows ensure that at least periphyton are monitored. Invertebrates and fish will also provide useful complementary information. If the problem involves potential toxic substances such as organochlorines, heavy metals etc. or organic contamination then ensure that invertebrates and fish are monitored. Periphyton can give useful indications (particularly early in the development of a problem) of the degree of labile organic matter contamination. Major changes in community structure/diversity are also good for indicating toxicity problems.

These *Guidelines* focus on the use of periphyton to indicate inorganic enrichment (and criteria to measure and manage problems associated with proliferations) so will not be considering toxicity biomonitoring further. This is because enrichment represents the main issue relevant to periphyton in New Zealand streams. Recent, more general, reviews of the application of periphyton for biomonitoring of water quality are given in Whitton et al (1991), Whitton and Rott (1996) and Lowe and Pan (1996).

There are two main sets of parameters: structural and functional. Structural parameters include biomass, diversity and community composition. Functional parameters include nutrient limitation assays, mat chemistry, relative growth rates and gross primary production. In a lucid review of the potential role of algae in environmental monitoring, McCormick and Cairns (1994) recommend the use of structural measures of algal condition rather than functional measures, which are often more time consuming and tend to be more sensitive to background environmental fluctuations unrelated to human disturbance. Of the structural parameters, McCormick and Cairns consider that more emphasis should be given to community-based taxonomic parameters (community composition, percent of sensitive taxa) than biomass because the taxonomic measures provide a more reliable estimate of ecosystem condition. This is particularly true in streams where periodic flooding and the sloughing of periphyton can result in dramatic fluctuations in biomass. In New Zealand, we have most experience with biomass measures followed by taxonomic measures; to a large extent, we now know how to work with these parameters within the context of flood disturbances. However, for completeness, both structural and functional measures will be reviewed in the following sections. Greater detail will be provided on structural parameters. For a wider discussion on the value of different periphyton variables see Stevenson (1996a).

7.2 Biomass: Inorganic enrichment/trophic status

Biomass is the biological outcome of differences in loss and gain mechanisms (see Section 4.2). When loss mechanisms such as sloughing at high flows and grazing by benthic invertebrates are minimal, then high concentrations of organic matter can accumulate on the stream bed. In general, a higher biomass will occur with higher nutrient supply providing that flow conditions are stable for long periods. However, there is high temporal variability in periphyton biomass in streams and thus it is necessary to carry out monitoring over a sufficiently long period that this variability can be characterised. Often it is the magnitude and duration of the periods of high (not just peak) biomass that are important.

For monitoring and resource evaluation purposes, the question then arises as to what constitutes a “low” (~ oligotrophic), “medium” (~ mesotrophic), and “high” (~ eutrophic) biomass. Various numbers have been arbitrarily suggested, using as a basis the range of values quoted in the literature (eg, 100–150 mg chlorophyll *a*/m^2; Horner et al, 1983) and frequency distributions of seasonal or annual mean chlorophyll concentrations (eg, Dodds et al, 1998). As noted in Section 6, Biggs (1995) developed trophic state designations based on the proportion of the catchments developed for moderate and high intensity agricultural production and rock type (thus, these were ‘mechanism’ rather than ‘effects’ based designations). Using data from Biggs (1995), oligotrophic streams were found to have a median monthly chlorophyll *a* of 1.7 mg/m^2 (1.5 mg AFDM/m^2); mesotrophic streams have a median chlorophyll *a* of 21 mg/m^2 (4.8 g AFDM/m^2); and eutrophic streams have a median chlorophyll *a* of 84 mg/m^2 (15g AFDM/m^2) (see Table 7) (Biggs, 1996a). The percentiles for periods of high biomass indicate that, for example, AFDM concentrations in oligotrophic streams are <6.0 g/m^2 for 90 percent of the year, <30g/m^2 for 90 percent of the year in mesotrophic streams and <190 g/m^2 for 90 percent of the year in eutrophic streams.

Table 7: Statistics for chlorophyll *a* and AFDM biomass distributions calculated from monthly samples for a year in four oligotrophic, six mesotrophic and six eutrophic gravel/cobble bed New Zealand streams (based on Biggs, 1995).

Parameter	Oligotrophic	Mesotrophic	Eutrophic
Chlorophyll a (mg/m^2)			
50th percentile (median)	1.7	21	84
75th percentile	3.0	60	260
90th percentile	20	100	600
Maxima	173	351	1396
AFDM (g/m^2)			
50th percentile (median)	1.5	4.8	15
75th percentile	3.5	12	40
90th percentile	6.0	30	190
Maxima	10.5	40	550

These data also illustrate the high variability of periphyton biomass. If we use 100 mg chlorophyll *a*/m^2 as a nominal high value for chlorophyll *a* biomass (following Horner et al, 1983 and the *1992 Guidelines*), we can see that oligotrophic streams can occasionally have high chlorophyll concentrations (with maxima over 150 mg chlorophyll *a*/m^2) and mesotrophic streams can spend up to 10 percent of the year with high chlorophyll concentrations (with maxima exceeding 300 mg chlorophyll *a*/m^2). Indeed, as noted in Section 3, most streams will have high periphyton biomass at some time of the year, but with increasing enrichment a stream will be prone to spending longer in such a state. So, for example, oligotrophic streams can spend approximately 2 percent of the year, mesotrophic streams ~10 percent of the year, and eutrophic streams ~ 50 percent of the year with a periphyton mats of >100 mg chlorophyll *a*/m^2.

Dodds et al (1998) extended the above analysis and compiled frequency distributions of mean and maximum seasonal chlorophyll *a* for over 170 stream sites in North America and New Zealand to determine the distribution of biomass values in streams. The objective of their study was to use these frequency distributions of chlorophyll as a guide to trophic status rather than using catchment conditions as done by Biggs (1995, 1996a). Dividing the distributions into thirds, Dodds et al suggested that the oligotrophic-mesotrophic boundary could be 20 and 60 mg chlorophyll *a*/m^2 for mean and maximum seasonal biomass respectively, and the boundary separating mesotrophic from eutrophic streams could be 70 and 200 mg chlorophyll *a*/m^2, respectively. The authors recognised that these values did not represent natural break points in ecosystem functioning along the enrichment gradient, but that they might serve as reference points for comparisons.

Considerable research is still required in this area. Some further discussion and guidance with respect to aesthetics, amenity value, contact recreation, the maintenance of "clean-water" invertebrate faunas, and angling are given in Section 8 of these *Guidelines*.

7.3 Autotrophic index: A measure of the degree of organic enrichment

Dissolved organic wastes (particularly sugars and low molecular weight organic compounds) tend to favour the growth of heterotrophic periphyton taxa such as the filamentous bacterium *Sphaerotilus natans* (sewage fungus). These communities can eventually outcompete autotrophic taxa (algae and cyanobacteria) and dominate biomass at high concentrations of dissolved organics creating nuisance slime growths that are unsightly and smother the streambed rendering it unsuitable for many other organisms (particularly some groups of invertebrates such as mayflies and stoneflies).

Historically, nuisance conditions have occurred downstream of discharges from some dairy factories, meat works, food processing industries and domestic sewage treatment plant outfalls. However, with increasing treatment of wastes in New Zealand (to remove the labile organic content), there has been a major decrease in the incidence of periphyton proliferations dominated by heterotrophic organisms. Nevertheless, some organic rich discharges do occur and can become quite concentrated in receiving waters during summer low flows.

A good measure to forewarn of an impending shift from a periphyton community dominated by autotrophic organisms to one dominated by heterotrophs is the autotrophic index (AI) (Collins and Weber, 1978). The index is simply determined as the ratio of AFDM:chlorophyll *a* (ensuring that both measures are in the same units). The greater the degree of organic contamination, the higher the value of the AI. Biggs (1989) used intensive monitoring over an accrual period to determine that the AI of communities on artificial substrates was highly correlated with the biochemical oxygen demand (BOD) in the water ($r = 0.962$, $P < 0.001$). Collins and Weber (1978) have suggested that once AI values exceed 400 then waters are starting to become impaired by pollution.

Several precautions need to be taken when employing the AI for monitoring of organic enrichment. First, there are considerable errors when measuring AFDM at low levels. Usually, much higher values of AFDM are recorded than actually occur because of a lack of sensitivity in the method. This can then result in a very high bias in AI values. Thus, AI should only be determined on samples with a reasonable biomass (eg, >2 g/m^2 AFDM). Second, some mucilaginous diatom and cyanobacterial communities can have naturally high AI values which could be misleading in data interpretation (particularly for control sites). For example, Biggs and Hickey (1994) recorded AI values of >2000 (documented as percent chlorophyll *a* in Biggs and Hickey) for a large number of samples from a thick *Gomphoneis/Cymbella/Synedra* dominated mucilaginous diatom community in the regulated Ohau River, South Canterbury, where no organic waste discharges occurred. Thus, it is important to ensure that plenty of biomass is collected for this analysis and that the community is not dominated by slime-forming diatoms (or cyanobacteria).

7.4 Percentage organic weight

Periphyton mats are very efficient at collecting silts (Graham 1988; Davies-Colley et al, 1992; Jowett and Biggs, 1997). Thus periphyton may be useful monitors of suspended solids concentrations in the water column. Percent inorganic weight (or silt) is simply calculated as the ratio of ash weight to dry weight. However, percent organic weight is the most commonly determined parameter, and this is determined as the ratio of AFDM:dry weight (eg, Davies-Colley et al, 1992) and is used as an indication of food quality of the periphyton mat for invertebrate grazers (Quinn et al, 1992; Biggs and Lowe, 1994).

High levels of silts in a mat are thought to reduce food quality for invertebrates (Graham, 1988; Ryan, 1991; Quinn et al, 1992). Biggs and Lowe (1994) reported a highly significant correlation between organic content and snail densities on artificial substrates in the Kakanui River, North Otago. Snail densities were greatly reduced where organic matter was less than 30 percent. Unfortunately, it is not possible to relate specific suspended solids concentrations to given levels of silt in periphyton mats (Graham, 1988) so that suspended solids criteria can be developed (deposition is a complex interaction between concentrations in the water, periphyton biomass and local water velocities; Jowett and Biggs, 1997). Nevertheless, percent organics can provide a useful relative measure such as comparisons between upstream and downstream of discharges or some other activity affecting a stream, such as gravel mining (Biggs and Lowe, 1994) or gold mining (Davies-Colley et al, 1992; Quinn et al, 1992).

7.5 Indicator taxa: Organic enrichment

Indicator taxa provide excellent signs of the direction and magnitude of ecosystem degradation. The use of indicators is a fundamental component of many enrichment and pollution evaluation systems that have been used extensively in Europe (Whitton et al, 1991; Whitton and Rott, 1996). This is in contrast to North America where diversity indices and more recently multi-metrics have been more widely used (McCormick and Cairns, 1994; Lowe and Pan, 1996). While regional calibrations of these indices may be necessary, available evidence suggests that algal metrics transfer reasonably well among geographic regions because most of the common taxa are cosmopolitan (McCormick and Cairns, 1994).

There are a number of benefits in using indicator taxa to assess stream degradation. First, many of the macroscopic indicators can often be readily recognised in the field enabling their early occurrence to be detected. This also enables evaluations to be made relatively cheaply. Second, this approach takes advantage of a wealth of autecological data/information on many of the taxa that has been accumulated elsewhere in the world (Lowe, 1974; Biggs et al, 1998d). Third, it does not require any sophisticated equipment or sampling. Much can be deduced using a good knowledge of periphyton ecology and a trained eye. However, these approaches also have their critics. The important thing to remember is that different situations often require different tools and thus it is important to have a "basket" of approaches to draw from.

One of the oldest indicator approaches is the saprobic system of classifying streams and rivers into zones of pollution from domestic and industrial discharges. This system was developed in Europe and is most commonly used there. Five broad zones of pollution impact are recognised, including clean water control locations upstream of any discharge points, two impact zones, a recovery zone, and a "purified" zone (Table 8). Broadly different periphyton communities are associated with each zone. These zones have also been characterised chemically so that some inferences can be gained on causes of the degraded conditions.

In New Zealand, the zone of highest impact (polysaprobic zone) will rarely (if ever) be present these days because discharge quality is now more strictly regulated by regional councils under the RMA. However, alpha and beta mesosaprobic zones can be expected in many streams below treated waste discharges. While the saprobic system cannot be used to indicate specific levels of pollution, it is a very useful general assessment tool that is valuable for rapid (field) identification of the general degree of organic pollution. Indeed, the detection of heterotrophic communities through microscope examination may be a more cost-effective and faster means of monitoring organic enrichment than using measures based on mass such as the autotrophic index (see previous section). More comprehensive reviews of this system are given by Sladecek (1979) and Biggs (1985).

Table 8: Gross water quality characteristics and associated periphyton communities along a river receiving organic enrichment according to the European Saprobic system (from Fjerdingstad, 1964).

Zone	Chemical	Periphyton Indicator Taxa
Oligosaprobic (clean water above an outfall)	BOD <3 g/m^3 High oxygen Mineralisation of organic matter is complete	Diatoms diverse, usually dominant Fil. green algae present Fil. bacteria scarce – absent
Polysaprobic (septic water immediately below an outfall with highly concentrated wastes)	H_2S high Oxygen low Ammonia high	Algae scarce Filamentous bacteria dominant *(Sphaerotilus, Zoogloea, Beggiatoa)*
α-Mesosaprobic (polluted)	Amino acids high H_2S low – absent O_2 <50 % saturation BOD >10 g/m^3	Algae scarce – some tolerant forms present such as *Gomphonema, Phormidium, Stigeoclonium, Euglena*. Filamentous bacteria still abundant
ß-Mesosaprobic (recovery zone)	$NO_3 > NO_2 > NH_3$ $O_2 > 50\%$ saturation BOD <10 g/m^3	High biomass of *Melosira, Gomphonema, Nitzschia* and *Cocconeis* diatoms. Diversity low. Cyanobacteria such as *Phormidium* and *Oscillatoria* are abundant. Filamentous green algae such as *Cladophora, Stigeoclonium* and *Ulothrix* are abundant.
Oligosaprobic (purified)	Stream recovered to clean water	Diatoms and N-fixing Cyanobacteria

A number of indices have been developed more recently in Europe to enable the changes in community structure to be summarised empirically. Some of these indices have been compared. Prygiel and Coste (1993) identified that certain indices are more sensitive to some types of contamination than others. None of these indices have been tested in New Zealand and this represents an area where some useful analysis could be carried out (perhaps using existing data). If necessary, a New Zealand index could be developed based on the taxa most commonly found here.

7.6 Indicator taxa: Inorganic enrichment/trophic status

In Section 7.2 trophic state classification using biomass was discussed. Traditionally, the trophic status of lakes was determined based on the taxonomic composition of the algae. A number of taxonomic trophic state indices for streams, based on periphyton diatom composition, have been developed in Europe (Coste et al, 1991; Kelly et al, 1995). Kelly and Whitton (1995) have developed and tested a new index of trophic state using a weighted averaging approach (trophic diatom index, TDI). The index is based on a suite of 86 taxa selected for their indicator value and ease of identification. When tested on 70 sites in Great Britain that were largely free of organic pollution, this index was highly correlated with aqueous phosphorus concentrations ($r^2 = 0.63$). This measure is simple to calculate and only requires enumeration of 200 diatom valves per sample. It is anticipated that it will pave the way for the development of more sophisticated metrics such has been done for invertebrates.

It is likely that this index would be useful for evaluating the trophic state of streams in New Zealand. However, a number of other taxa commonly found in New Zealand would need to be added to Kelly and Whitton's indicator list, including many soft bodied algae which often dominate our streams in summer. Table 9 lists taxa commonly found in New Zealand periphyton communities and their inorganic enrichment indicator value. One tick denotes reasonable indicator value, two ticks denotes good indicator, and three ticks denotes a very good indicator (ie, these taxa have very specific habitat requirements). This listing provides guidance for the rapid trophic classification of streams and could form the basis for a stream periphyton trophic state indicator system for New Zealand. This is an area requiring further study.

Table 9: Trophic designations of some taxa commonly found in New Zealand periphyton communities (developed from Biggs and Price, 1987; Biggs, 1990a, 1995; Kelly and Whitton, 1995; Biggs et al, 1998d; Biggs, unpublished data; S. Moore, unpublished data). Note that the habitats listed for each taxon are where that taxon is most likely to dominate communities or be abundant. However, many taxa (particularly diatoms), can be found as subsidiary components of mats in other environments.

Taxon	Oligotrophic	Oligotrophic – Mesotrophic	Mesotrophic	Mesotrophic – Eutrophic	Eutrophic
Diatoms					
Achnanthidium lanceolatum[1]					✔✔
Achnanthidium minutissimum[2]	✔✔				
Achnanthidium spp·			✔		
Cocconeis placentula	✔	✔✔	✔✔✔	✔✔	✔
Cymbella affinis/kappii		✔✔			
Cymbella minuta			✔✔		
Diatoma vulgare					✔✔✔
Diatoma hiemale var. mesodon	✔✔	✔✔			
Diatoma sp.		✔			
Epithemia sorex	✔✔	✔✔			
Epithemia sp.	✔✔				
Eunotia sp.	✔✔✔				
Fragilaria capucina		✔✔			
Fragilaria construens			✔✔		
Fragilaria vaucheriae			✔✔		
Fragilaria sp.		✔			
Frustulia sp.	✔✔				
Gomphoneis minuta var. cassieae[3]		✔✔	✔		
Gomphonema angustatum	✔✔				
Gomphonema olivaceum					✔✔✔
Gomphonema parvulum					✔✔✔
Gomphonema sp.			✔		
Gyrosigma spp.					✔✔
Melosira varians				✔✔	
Meridion circulare		✔✔✔			
Navicula avenacea		✔✔			
Navicula cryptocephala			✔✔		

Taxon	Oligotrophic	Oligotrophic – Mesotrophic	Mesotrophic	Mesotrophic – Eutrophic	Eutrophic
Neidium sp.		✔✔✔			
Nitzschia acicularis			✔		
Nitzschia dissipata				✔✔	
Nitzschia palea				✔✔	
Nitzschia spp.				✔	
Pinnularia spp.				✔✔	
Rhoicosphenia curvata				✔	
Rhopalodia sp.	✔				
Synedra ulna			✔		
Synedra rumpens			✔		
Green algae					
Bulbochaetae sp.	✔✔	✔✔			
Cladophora glomerata				✔	✔✔
Cladophora sp.			✔✔		
Microspora sp.			✔✔✔	✔✔	
Mougeotia sp.		✔✔	✔✔✔		
Drapanaldia sp.	✔✔				
Oedogonium spp.		✔✔	✔✔✔		
Rhizoclonium sp.					✔✔
Spirogyra spp.			✔✔		
Stigeoclonium lubricum			✔✔		
Ulothrix zonata		✔✔			
Chrysophytes					
Vaucheria sp.			✔✔		
Cyanobacteria					
Calothrix sp.	✔✔✔				
Lyngbya sp.	✔✔	✔✔✔	✔✔	✔	
Nostoc sp.	✔✔✔	✔✔	✔		
Phormidium sp.		✔	✔✔	✔	
Schizothrix calcicola			✔✔		
Stygonema sp.	✔✔✔				
Tolypothrix sp.	✔✔✔	✔✔✔	✔		
Red algae					
Audouinella hermanii	✔✔✔	✔✔	✔		
Batrachospermum sp.	✔✔				

Notes:

[1] Previously known as *Achnanthes lanceolata*

[2] Previously known as *Achnanthes minutissima*

[3] Previously known as *G. herculeana*

7.7 Community diversity: a measure of the balance in population structure

Diversity indices have been developed and used fairly extensively in North America. These indices have two components: taxonomic richness (ie, the total number of taxa) and evenness (ie, the relative number of individuals spread among those taxa). A range of formulas have been proposed. Probably the most widely used is the Shannon-Weaver index, although Simpson's Index is recommended because it is less sensitive to large numbers of taxa with few individuals. In reality these two indices are usually highly correlated so it may not matter which is used (Biggs, unpublished data). With the introduction of a pollutant to nature (eg, phosphorus or nitrogen to a stream), one of two taxa are able to grow well under the modified conditions whereas other taxa either cannot compete or they are directly detrimentally affected by the pollutant. This usually results in a reduction in diversity evenness as the taxonomic structure of the community is simplified.

There has been considerable debate as to the use of such diversity indices in pollution assessment. This is largely because there is still not a clear understanding of the ecological significance of different levels of evenness. This is now the subject of intense research. The assumption has historically been that high diversity is "good" and any reductions (eg, through a waste discharge) are "bad". Apart from the loss in taxa that this may indicate, the suggestion has been that a reduction in diversity will result in a reduction in the number of functional processes, and thus a reduction in system stability and ability to resist natural and anthropogenic disturbance. Recent research has not clearly resolved this debate.

To obtain reliable estimates of diversity (particularly evenness) in stream periphyton samples requires fewer samples from a site than for biomass estimates. For example, mean Shannon-Weaver diversity of communities on artificial substrates can be estimated to within 20 percent with only two replicates, whereas over 20 samples are required for a similar level of precision for chlorophyll *a* and >40 replicates are required for algal density (Biggs, 1988b). However, while fewer replicates might be needed for determining diversity, quite large numbers of individuals per replicate may need to be counted under the microscope for detailed statistical analysis (eg, 300–500 cells per replicate sample; Lowe and Pan, 1996) and this can become quite time consuming.

Algal diversity has only been used once in periphyton stream monitoring studies in New Zealand. Biggs (1989) determined Shannon-Weaver diversity indices for samples from artificial substrata on two occasions upstream and downstream of a gross organic waste discharge in the South Branch of the Waimakariri River near Christchurch. On the first occasion there was no significant difference in diversity as a function of the discharge even though it resulted in nuisance growths of sewage fungus and high densities of pollution tolerant diatoms in the downstream reach. However, on the second occasion (three weeks later) diversity was significantly reduced below the outfall. This illustrates another concern that is often voiced in using diversity for pollution monitoring. This is that in reducing community structure down to a single number there is a major loss of very important information about the actual species composition of the community which is often far more important than the diversity index result. Also, major species replacements can occur in situations with pollution involving enrichment (organic or inorganic) which may result in no significant change in diversity. Indeed, diversity evenness can even increase in such circumstances.

7.8 Multivariate statistical analyses

Instead of determining differences in abundance of indicator taxa or calculating diversity indices from community enumerations, a recent trend for many ecological analyses has been the use of multi-variate statistics. This enables complex data to be decomposed into groups of taxa, or scores, that behave similarly. Changes in the location of these groups among sites, or at a single site over time, are then related to gradients in environmental conditions or a specific variable known to influence community structure (eg, temperature). Such approaches are being increasingly used for algal pollution assessment to determine most likely causes of community change. This approach is particularly useful in identifying possible factors influencing communities where there may be synergistic effects or the exact causal variables are unknown, and to determine the effects of non-point source pollution. Table 10 summarises common approaches and their attributes.

Table 10: Multivariate analyses commonly used in ecological studies and biological monitoring/ resource assessments. This is not an exhaustive list.

Method	Attributes	Comment
Grouping similar sites		
Cluster analysis– general community aggregations	2-step process. Similarities in community composition are determined using one of a number of different methods including correlation analysis. Similarity indices are then grouped and displayed in a dendrogram using a linking algorithm. Benefits include giving a visual display of the differences in overall community structure whereby the proximity of one community/site to another in the dendrogram is proportional to the similarities/ differences in community composition	A good method for screening data and visually displaying community associations. It is important to decide on whether similarity or dissimilarity indices are more appropriate to use. Different linkage algorithms can give very different groupings for sites/communities. Several should always be tested and the one giving the most ecologically sensible result used. It is difficult to determine the statistical significance of community differences displayed in dendrograms.
Cluster analysis– indicator taxa (eg, TWINSPAN)	TWINSPAN is a divisive technique whereby the entire dataset is first split into two groups that have maximum difference between them, and then these groups are divided further, based on smaller differences. The divisions are based on the relative abundance of indicator taxa. These taxa are then defined for the user.	Important to carefully define ecologically meaningful pseudospecies weightings. Also, the indicator species upon which divisions are being made may be quite rare and thus community divisions may have only marginal relevance to management issues. This method has become the most popular clustering technique among ecologists for research because of the information given on indicator taxa.

Method	Attributes	Comment
Arraying sites along environmental gradients		
Principal components analysis (PCA)	Sites arranged in 2- or 3-dimensional space according to similarities in taxonomic composition. Principal component scores can be correlated with relative abundances of taxa to see what combinations of taxa they represent. Principal component scores can also be correlated with environmental variables to determine correspondence with environmental gradients.	Groups taxa that are highly correlated (positively or negatively) in abundance and treats them as a single entity or group. Very useful for tracking changes in community composition at single sites over time. Called a "2-step, indirect, gradient analysis"; Lowe and Pan, 1996). This technique requires data that is approximately normally distributed. It is a popular technique with many ecologists.
Detrended correspondence analysis (DECORANA)	DECORANA is an ordination technique that is based on reciprocal averaging. Unlike ordinary reciprocal averaging, this method does not produce any 'arch artifacts' in the resultant ordination. It ordinates both sites and species simultaneously. In this way, samples can be plotted in species space, so that closely clustered samples contain similar species groupings. Species can also be plotted in sample space, so that closely clustered species groups come from the same samples.	DCA is very popular with stream ecologists. Although there was concern about its stability on some data sets, most of these related to older versions of the programme, and have been ironed out in modern versions. Commonly used packages include PC-Ord and CANOCO.
Multiple discriminant analysis	Sites are first grouped according to similarities in species composition. These site/community groups are then related to weighted linear combinations of the environmental variables to develop discriminant functions. These empirical functions can then be used to predict the type of community that should occur at a site based on local habitat conditions if the discriminant functions are able to explain a high amount of variance.	A widely used technique in some fields of ecology (eg, the RIVPACS methodology developed in Great Britain for assessing degree of stream degradation using macroinvertebrates). The method has been tested in the New Zealand "100 Rivers" study. The method needs a good database covering a wide range of conditions to develop robust discriminant functions.
Canonical correspondence analysis (CCA)	Combines ordination with multiple regression analyses. Axes are linear combinations of environmental variables against which species distributions are regressed. Detects patterns in species related to physical and chemical parameters. Assumption is that species respond to environmental gradients in a unimodal manner.	Uses specially developed program called CANOCO. Technique first developed in late 1980s, but has become very popular in general ecology because it is powerful at detecting species-environment associations. Called "direct gradient analysis" (Lowe and Pan, 1996).

Most of the above methods have been used to analyse periphyton data in ecological studies, but only rarely have they been used to help resolve water resource management or planning issues. A major effort was made in the New Zealand "100 Rivers" studies to develop multiple discriminant models (similar to those developed for the British RIVPACS invertebrate protocol; Wright et al 1989) to enable water quality, periphyton, invertebrate and fish communities to be predicted from environmental variables (Biggs, 1990a; Biggs et al, 1990; Close and Davies-Colley, 1990; Jowett, 1990; Quinn and Hickey, 1990). This could then serve as a basis for predicting and assessing the effects of different water resources management options/plans.

However, it was found in a validation analysis that the predictive power of these models was quite limited and they were insensitive to modest changes in individual predictor variables that could be important limiters of community development. It was therefore concluded that "discriminant models are not likely to be a useful approach for assisting water management" in New Zealand (Biggs et al, 1990). Several reasons could account for the poor performance of discriminant models in this study. First, the calibration dataset covered a very wide range of habitat types so that the most important controlling variables are likely to have changed among these habitats. Second, a large number of the sites had been impacted by flood disturbance within the study period and thus the communities were at various stages of regeneration and may not have accurately reflected local habitat conditions.

Further work should be attempted using canonical correspondence analysis. This technique has been valuable in other branches of ecology to relate species to environmental gradients/ perturbations and is likely to contribute greatly to understanding and predicting periphyton distributions in New Zealand streams.

7.9 Rapid assessment protocols

Rapid bio-assessment methods for use in the field have been developed in North America for invertebrates (Plafkin et al, 1989). A rapid assessment protocol for both invertebrates and periphyton was recently developed for New Zealand (the SHMAK protocol; Biggs et al, 1998c). This enables broad differences in cover of different mat types (as defined by colour, thickness and filament length) to be documented, scored and related to a table of information describing what various scores might represent in terms of stream health and habitat conditions.

For the SHMAK protocol, it is recommended that sampling not be carried out until there have been at least three weeks of low flows, so that communities have sufficient time to develop following disturbance. (This may not be long enough in gravel bed rivers with very mobile sediments.) At least ten stones (or points) are examined on the stream bed (five stones on each of two transects across the streams) and the percentage cover of periphyton in 11 categories is estimated for each stone. These values are then averaged across all 10 stones/points examined and multiplied by a weighting factor that reflects the degree of enrichment/habitat degradation that the community is likely to be reflecting (see the technical manual).

7.10 Functional responses

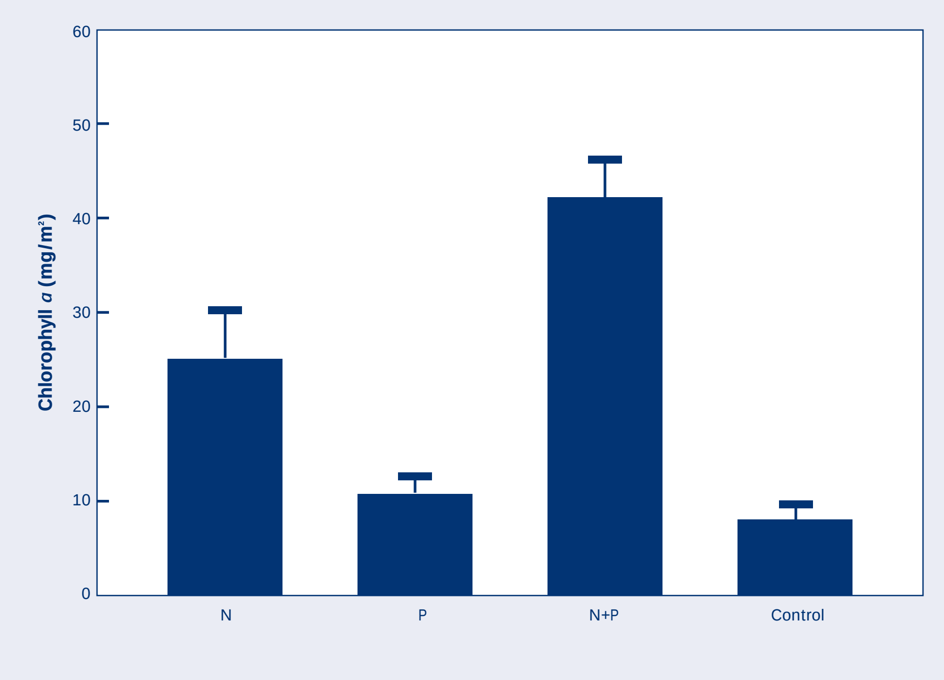
There are a range of functional responses that can provide useful insights into the quality of the stream environment, and the type and extent of enrichment/pollution. These include instream nutrient limitation assays, cellular nutrient concentrations, relative growth rates and gross primary production.

7.10.1 Instream nutrient limitation assays

The use of instream nutrient diffusing substrate (NDS) bioassays has become very popular for determining whether periphyton communities are nutrient limited, or not, and if so, which nutrient is in shortest supply. This technique, developed in the United States by Fairchild and Lowe (1984) and Pringle and Bowers (1984), has been widely used in New Zealand, with the added development of also determining relative nutrient limitation by comparing the effects of enrichment:control chlorophyll *a* biomass among sites (Francoeur et al, 1999). The method involves placing replicate containers of agar impregnated with nitrogen or phosphorus into streams and allowing these nutrients to diffuse from the agar through a porous clay tile or hardened filter paper upon which the periphyton grow (see the technical manual).

The treatment with the highest biomass indicates the nutrient that is in shortest supply (Figure 26). A higher biomass on the nitrogen-enriched substrata compared with the control indicates that the growth of periphyton on the stream bed during interflood periods is likely to be limited by a shortage in nitrogen. The much greater response to nitrogen plus phosphorus suggests that with the addition of nitrogen, phosphorus then becomes limiting and therefore indicating that there are not high quantities of surplus phosphorus in the stream. If no nutrient stimulation occurs, then either nutrients are adequate for periphyton growth, or some other factor such as invertebrate grazing is restricting biomass accumulation.

Figure 26: Example of the results of a nutrient diffusing substrate experiment in a hill country river (Kauru River, Otago). Vertical bars denote standard errors.



Extensive studies in both the North and South Island using nutrient diffusing substrata and mat nutrient chemistry have found that periphyton communities in the majority of streams where they flow from undeveloped forest or tussock lands are nitrogen limited (Biggs, 1995; Biggs et al, 1998b; Quinn et al, 1997b; Francoeur et al, 1999; Biggs and Francoeur, unpublished data). It is clear that moderate concentrations of phosphorus occur naturally in many of our streams as a result of leaching of nutrient-rich rocks such as recent volcanics and marine Tertiary mudstones and sandstones (Biggs, 1990a, 1995; Close and Davies-Colley, 1990).

Recent research using NDS assays at 15 sites covering 14 South Island streams (Biggs et al, 1998b; Francoeur et al, 1999) has indicated that nutrient limitation assessments in late autumn and winter do not give particularly reliable results because of very low, probably temperature limited, periphyton growth rates. However, assays carried out in spring or summer and early autumn are useful and tend to give consistent results among the seasons.

7.10.2 Mat nutrient chemistry

It is now well accepted that algal mat chemistry plays a stronger role than water column chemistry in periphyton biology (Lowe, 1996). Concentrations of nutrients dissolved in the water may not be a reliable indicator of the degree of nutrient limitation, or nutrient supply regime to periphyton (Biggs, 1995) (see Section 4.3.2). This is because the source of nutrients during stable/low flows in natural gravel bed streams is often, if not mainly, via seepage up from groundwater or in from subterranean seepages at the edge of the stream. As this more enriched water enters the sunlight regime of the open stream, the periphyton begins stripping the nutrients from the water. Thus, what is measured in bulk water samples is just what is surplus to the periphyton's requirements or is being recycled downstream.

Conversely, the concentration of nitrogen and phosphorus within the mat reflects these supply concentrations. Both cellular nitrogen and phosphorus are determined by digesting and analysing samples as for total nitrogen and total phosphorus analysis of water samples, but then dividing the mass of nitrogen and phosphorus by the organic quantity of the sample (as grams AFDM) and expressing the results as percent nitrogen and percent phosphorus. These concentrations vary from 1 – ~9 percent for nitrogen and 0.05 – ~0.5 percent for phosphorus, depending on the degree of limitation of growth.

Mat nitrogen concentrations tend to be <3 percent in streams with forested catchments and hard, nutrient poor rocks (eg, greywacke, schist etc.); 3–5 percent in streams with some catchment development and moderate amounts on nutrient rich basement rocks; and >5 percent in streams with intensive catchment development and/or extensive areas of nutrient rich basement rocks. Communities showing phosphorus limitation of growth tend to be in the downstream reaches of larger rivers flowing across extensively developed gravel plains where nitrate enriched groundwater may form an important contribution to flows during summer (Freeman, 1986; Biggs and Close, 1989; Biggs and Lowe; 1994). In general, control of phosphorus (eg, from fertilisers) is likely to be easier than nitrogen as a means of reducing periphyton proliferations in downstream reaches of rivers because nitrate is usually present at moderate–high concentrations (and is highly mobile).

7.10.3 Relative growth rates

It is possible to determine the relative degree of growth rate limitation by nutrients by using chlorophyll *a* accrual rates on artificial substrate samplers. This can be a useful tool for determining the effects of point source discharges (Biggs, 1990b). The maximum (ie, nutrient saturated) net periphyton growth rate (μ_{max}) is calculated from mean water temperature data over an accrual period at sites and then the growth rate recorded in the field at any given site is calculated as a proportion of the maximum growth rate (ie, $\mu:\mu_{max}$) giving a measure of the relative degree of nutrient limitation. For phosphorus-limited communities, values for this ratio of <0.3 (ie, growth is <30 percent of the maximum possible for the given temperature) have been suggested to indicate severe nutrient limitation whereas values >0.8 (ie, growth is >80 percent of the maximum possible for the given temperature) indicate no nutrient limitation of growth (Bothwell, 1985). While these criteria have been developed for phosphorus-limited communities, they are probably also applicable for evaluating degree of nitrogen-limitation of communities because they are criteria based on temperature limited growth rate maxima and not specific nutrient supply criteria.

7.10.4 Gross primary production

The use of gross primary production (GPP) or maximum primary production (Pmax) is usually confined to research studies in New Zealand, because it is equipment- and labour-intensive. However, these variables can provide useful data when, for example, the overall effects of specific driving variables on autotrophic production is being assessed such as light, velocity or river morphology (Biggs and Hickey, 1994; Young and Huryn, 1996; Quinn et al, 1997b). In general, Pmax correlates with chlorophyll *a* biomass so may not provide much greater information than chlorophyll *a*. In some limited situations these production measures may complement other periphyton measures of stream degradation.

One of the best examples of the use of primary production for pollution assessment in New Zealand streams is that described by Davies-Colley et al (1992) where benthic chambers were used to determine the effects of fine suspended solids discharges from gold mining operations on periphyton communities in a selection of West Coast streams. Primary productivity, together with percent organic content of the mat and chlorophyll *a*, enabled a definition of the smothering effect of the settled clays and how this influenced the primary productivity of the system.

8 Guidelines for protecting instream values from enrichment effects

Instream values form the basis for developing different instream management objectives (ISMOs). The needs of some generic values (and thus ISMOs) in relation to periphyton are discussed here, including:

- limits on the amount of periphyton for different instream values
- setting limits in relation to the habitat type
- nutrient supply concentrations to achieve these limits, and
- baseline and compliance monitoring.

While periphyton have a major role to play in environmental monitoring and bioassessment, most management issues relate to enrichment and associated proliferations of periphyton. For example, low periphyton production may limit the overall productivity of the ecosystem (and thus influence the carrying capacity for trout). This is not addressed here because most concerns relate to proliferations.

The type of periphyton dominating the community has a bearing on environmental effects, which is an important aspect of determining different criteria appropriate to the maintenance of different instream values. For example, periphyton mats dominated by filamentous green algae are far more conspicuous than diatom-dominated mats for a similar biomass. Therefore the following proposed limits on periphyton biomass are given in terms of diatom/cyanobacterial mats and filamentous green algal mats.

8.1 Suggested limits on amounts of periphyton for different instream values

A list of instream values that can potentially be affected by excess periphyton biomass was given in Table 3. Of these 13 instream values we are currently only able to develop criteria in relation to aesthetics, biodiversity, angling and contact recreation. The requirements for aesthetics and contact recreation are probably very similar so shall be grouped as ‘amenity values’ in the following assessment. *Note that the guidelines suggested below have not yet been fully tested. Therefore, until further research has been carried out, they should be treated as provisional.*

8.1.1 Biomass and cover criteria in relation to amenity values

Aesthetic appreciation and the needs for contact recreation such as swimming have not been objectively defined and are likely to vary greatly among individuals. Probably the most significant issue is the visual degradation of stream environments by filamentous green algae and the aversion of swimmers to slime on rocks. These slimes are most commonly produced by diatoms such as *Gomphoneis minuta* var. *cassieae*. But what is a significant amount? Some indication can be gained from what can occur naturally in unenriched rivers. Often there are individual stones that have thick slimes in such rivers (Figure 27). However, when such slimes exceed approximately 60–70 percent of the river bed over a reach, then the slime is likely to be quite conspicuous, and it would detract from contact recreation values, such as swimming. A conservative value of 60 percent cover of a reach by thick diatom slimes (ie, >0.3 cm), during periods when recreational use is likely (eg, 1 November–30 April) can be used as a guideline.

Figure 27: Stone with a thick diatom mucilage dominated by *Gomphoneis* and *Cymbella*. The olive green filaments are formed by the chain-forming diatom *Fragilaria*, Baton River, Northwest Nelson.

Green or brown filamentous algae tend to cause more problems for contact recreation and are more conspicuous than diatom mats and slimes because of their coloration and the way the filaments extend up into the water column. Filamentous algae tend to become entangled around feet, on clothes and limbs while swimming. Such conditions can be annoying to the public and reduce amenity value greatly. While no evaluation exists of what constitutes "too much" filamentous algae for the general public, Biggs and Price (1987) observed that such mats became very conspicuous from the bank of shallow streams when they exceeded 40 percent cover. At this point the overall "ambience" of a stream scene appeared to be significantly compromised (Figure 28). This value was accepted for use as a guideline in the *1992 Guidelines*.

Wider experience since the development of that guideline suggests that 40 percent is too high for many water users. In part, this is because the filamentous algae are most often concentrated in the low velocity peripheral areas of shallow streams where public activity is also concentrated. Further, when the focus of activities is contact recreation in the stream (eg, for children's bathing) rather than just as a general part of the landscape, then greater attention is given to what is on the bed and even modest amounts of filamentous algae can become undesirable. Thus, a maximum of 30 percent cover of a reach by filamentous green or brown algae is now recommended as a guideline for the protection of aesthetic and contact recreation values in streams during periods when recreational use is likely. In terms of average reach biomass, this is approximately 35 g AFDM/m^2 (~ 120 mg chlorophyll *a*/m^2) of filamentous green algae.

Note that this evaluation relates to shallow reaches of streams (ie, <0.75 m deep), and that once depths are much greater then it is difficult for an observer to see the bed and associated periphyton. In such situations it is the peripheral zone that is most important to human perception. These criteria are also expressed in terms of reach-averaged cover for the specified depth zone. A reach is defined as a relatively homogeneous section of stream channel. Most commonly this will be a run or a pool, but should be clearly specified in setting consent conditions (whether for cover or biomass). Also, the most relevant time for human usage is summer (1 November–30 April). Therefore, a qualifier needs to be added to the guideline, of "*during periods when recreational use is likely*". It would be most sensible to only apply the amenity guidelines during such times.

Figure 28: Gradient in percentage cover and biomass of filamentous algae, Waipara River, North Canterbury.

20% cover, 80 mg chl. a/m^2, 25 g AFDM/m^2

30% cover, 120 mg chl. a/m^2, 35 g AFDM/m^2

40% cover, 160 mg chl. a/m^2, 40 g AFDM/m^2

55% cover, 300 mg chl. a/m^2, 50 g AFDM/m^2

70% cover, 900 mg chl. a/m^2, 200 g AFDM/m^2

95% cover, 640 mg chl. a/m^2, 90 g AFDM/m^2

Several researchers have proposed biomass criteria for filamentous green algae in relation to requirements of contact recreation and aesthetics (Horner et al, 1983; Welch et al, 1989). These have all been determined subjectively and included a wide range of values (50–200 mg chlorophyll *a*/m^2, Table 11), but are most commonly in the range of 100–150 mg chlorophyll *a*/m^2. Such biomass values were adopted for the, 1992 New Zealand guidelines independently of the cover criterion, and are similar to what is being proposed in the present guide.

Table 11: Suggested criteria from various studies for maximum periphyton biomass to avoid problems for recreational and aesthetic use of streams (from Dodds et al, 1998).

Suggested value or range (mg chl. a/m^2)	Comment	Source
150-200	Based on perceived impairment	Welch et al, 1989
100-150	Based on, 19 enrichment cases and surveys	Welch et al, 1988; Horner et al, 1983
150	Guidelines for Clark Fork River, Montana, USA	Tristate Implementation Council (as cited by Dodds et al 1998)
50-100	British Columbia , Canada, environment guideline	Nordin, 1985

However, because these biomass criteria have only been arrived at subjectively it would be worthwhile to carryout a quantitative study to define human perception of algal proliferations and what might constitute “too much” algae for recreational and aesthetic use of streams.

8.1.2 Biomass guidelines in relation to maintenance of "clean-water" benthic fauna and benthic biodiversity

A change in benthic invertebrate community structure with increasing periphyton biomass has been a common observation in New Zealand streams (Towns, 1981; Quinn and Hickey, 1990; Quinn et al, 1996, 1997a, b). In particular, a shift from faunas typifying "clean waters" to those typically found in organically degraded conditions has been widely observed as a function of enrichment (Quinn and Hickey, 1990). For example, the mayfly *Deleatidium* favours relatively "clean" rock surfaces, whereas orthoclad chironomids prefer thick periphyton mats into which they burrow (Winterbourn, 1986; Quinn et al, 1996). These general changes in invertebrate community composition with increasing enrichment can be demonstrated clearly with invertebrate data from the streams previously classified in Table 7 as oligotrophic, mesotrophic and eutrophic in (Table 12).

Table 12: Relative abundances of main invertibrate groups in New Zealand streams according to trophic state (data derived from Quinn and Hickey 1990, and Biggs 1995). The invertibrate data is from one sampling (seven replicates) in late summer.

Parameter	Oligotrophic	Mesotrophic	Eutrophic
Chlorophyll a (mg/m^2)			
90th percentile	20	100	600
AFDM (g/m^2)			
90th percentile	6.0	30	190
Invertebrates			
Stonefly nymphs–predators	Pres. – Com.?	Pres.	Abs.
Stonefly nymphs- collector/browsers	Dom.	Abs.	Abs.
Mayfly nymphs–collector/browsers	Dom.	Dom. – Pres.	Pres.
Caddis larvae – filter feeders	Com.	Com. – Dom.	Com. – Dom.
Caddis larvae – collector/browsers	Dom.	Com. – Dom.	Com.
Caddis larvae–predators	Pres.	Pres.	Pres.
Snails	Abs.	Abs. – Com.	Com. – Dom.
Midge larvae	Pres.	Com.	Dom.
Beetle larvae – collector/browsers	Pres.– Com.	Com. – Dom.	Dom.
Oligochaete worms	Pres.	Pres. – Com.	Com.

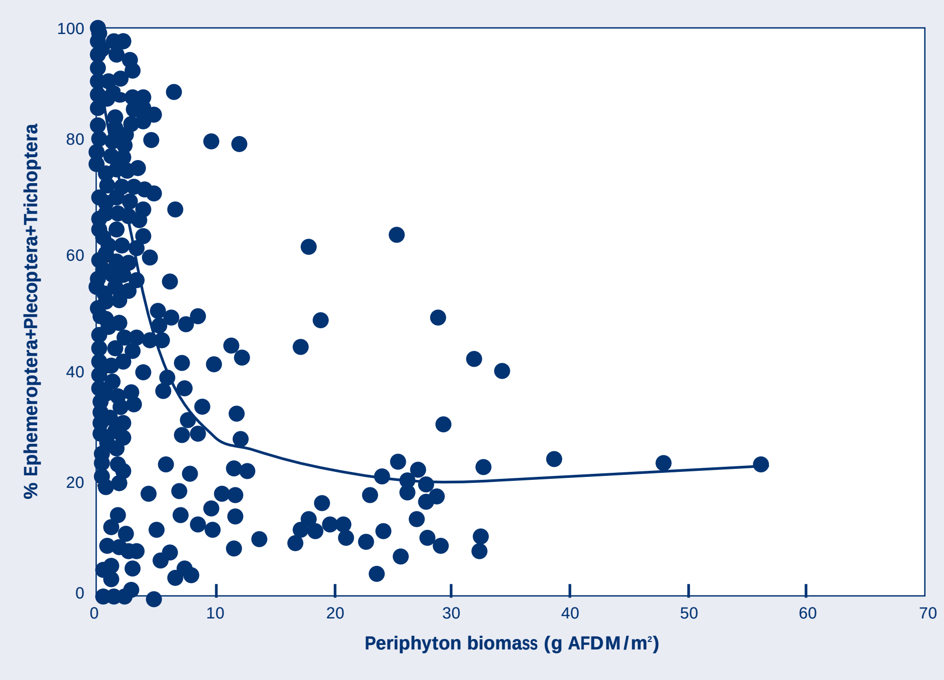
Dom. = abundant or dominant in the streams; Com. = common; Pres. = present in relatively low numbers; Abs. = generally absent.

Table 12 demonstrates that, at the extremes, oligotrophic streams tend to be dominated by collector/browser stoneflies, mayflies and caddisflies. Whereas, eutrophic streams tend to be dominated by filter-feeding caddisflies, snails, collector/browser beetles and oligochaete worms, a fauna often taken to represent organically enriched conditions (Stark, 1985; Quinn and Hickey, 1990). The mesotrophic streams had a somewhat intermediate invertebrate assemblage and some groups had a wide range of relative abundances. Of particular interest is the major reduction in importance of stoneflies and mayflies with increasing trophic status.

While useful in defining the type and extent of change in ecosystem properties with increasing periphyton production, the data presented in Table 12 (and indeed in most previous periphyton/ invertebrate studies) does not provide explicit definition of when ecosystem degradation is likely to occur in relation to periphyton biomass. Ideally we need to define thresholds in ecosystem structure and function with increasing periphyton biomass and then use these to define management criteria.

Data from paired periphyton–invertebrate samples collected at 31 sites in 21 New Zealand streams were compiled from existing databases (Biggs, unpublished data, and A.M. Suren, pers. comm.) to determine whether thresholds in community composition as a function of periphyton biomass could be defined. Figure 29 shows percentages of the invertebrate community composed of taxa generally considered to indicate "clean waters" (ie, mayflies, stoneflies and caddis flies) in relation to periphyton AFDM.

Figure 29: Relative abundance of "clean water" EPT invertebrates (Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies)) as a function of the ash-free dry mass of periphyton in the samples. The line of "best-fit" was determined using distance-weighted least squares regression. Most periphyton samples were dominated by diatoms (*Gomphoneis, Cymbella, Synedra*) and filamentous cyanobacteria (*Phormidium*).



While there is much scatter in the data, this analysis more clearly shows that the relative abundance of "clean water" invertebrates is linked with periphyton biomass. This analysis indicates that the average composition of the community as EPT taxa decreases sharply to below 50 percent where periphyton biomass exceeds ~ 5 g AFDM/m^2 (~ 13 mg chlorophyll *a*/m^2). Conversely, the relative abundance of midges, worms and snails increases greatly above this level of periphyton biomass (data not shown for brevity). While a low periphyton biomass does not guarantee that the invertebrate community will be dominated by EPT taxa (because other factors can also limit species representation in any given sample, such as flood disturbance, temperature etc.), high proportions of EPT taxa were only found where periphyton biomass was low. Conversely, only low proportions of EPT taxa occurred where periphyton biomass was high.

An analysis was also carried out to determine whether invertebrate diversity varied significantly as a function of periphyton biomass. The number of invertebrate taxa per sample varied over the range of 1 to 40 at low periphyton biomass (ie, <5 g AFDM/m^2). However, above this biomass, the range reduced to 14–30 taxa and this did not change significantly with increased periphyton biomass. Similarly, there was a large range in the Shannon-Weaver index of diversity evenness at low periphyton biomass of 0.1–3.8. However, the range reduced to ~ 1.5–3.0 at higher periphyton biomass, with no trend.

The preceding analysis suggests that average periphyton biomass should be kept to < ~ 5 g AFDM/m^2 (ie, ~ 13–20 mg chlorophyll *a*/m^2) of sediment surface exposed to the light (as a reach average, with a reach most commonly being a run) to maintain an invertebrate community dominated by "clean-water" invertebrates. While these values are low, they are typical of the mean monthly biomass in streams draining undisturbed forest and alpine catchments in New Zealand (Biggs and Close, 1989; Biggs, 1990a, 1995; Biggs et al, 1998b, 1999) and within which there are diverse invertebrate communities with a high proportion of EPT taxa (Table 12 and Biggs unpublished data).

It also needs to be recognised, however, that such streams have short periods of peak biomass which are much higher than the above values, but which do not appear to cause much long-term degradation of the benthic faunas. To better identify the levels of these peaks, an analysis was done of the peak biomass of 16 oligotrophic streams where diverse, "clean-water", benthic invertebrate communities existed (Biggs unpublished data). These included the four streams used in Table 12, plus a further 12 streams sampled monthly for 15 months with forest or snow tussock catchments (see Biggs et al, 1999). The average in peak biomass recorded from these 16 streams was 47 mg chlorophyll *a*/m^3. The periods of higher biomass usually only occurred on single sampling occasions suggesting that they lasted for relatively short periods, such as during spring blooms of the filamentous green alga *Ulothrix zonata*. Based on these considerations, I recommend that the mean monthly biomass not exceed 15 mg chlorophyll *a*/m^2 and the peak biomass not exceeded 50 mg chlorophyll *a*/m^2 for the protection of benthic biodiversity in streams. These values are similar to mean and maximum biomass values found by Dodds et al (1998) to delineate the lower and middle third of their chlorophyll frequency distribution (their values being 20 and 60 mg chlorophyll *a*/m^2), and which they suggested could be used as a boundary between oligotrophic and mesotrophic streams. The present guideline for benthic biodiversity is only given in terms of chlorophyll *a* because AFDM is more prone to large measurement error with low biomass accrual.

While the diatom/cyanobacterial guidelines will be applicable to the majority of New Zealand streams, there are also a significant number of streams that are prone to filamentous green algal blooms. However, the relationship between the biomass of filamentous green algae and invertebrates is poorly defined and requires considerably more research. Field observations suggest that changes in invertebrate communities occur at a more modest biomass than with diatom/cyanobacterial mats. For example, Biggs and Stokseth (1996) reported from a Canterbury gravel bed river (Okuku River) that as a diatom-based community was progressively overtaken by a *Spirogyra* and *Oedogonium* filamentous green algal community forming a total biomass of >20 g AFDM/m^2, a shift occurred from a dominance of caddis larvae to chironomid larvae, with caddis having a lower relative abundance. When the matrix later sloughed (at a biomass of >30 g AFDM/m^2) the invertebrate assemblage started to become dominated by caddis and mayflies again. In the absence of any more specific research on the effects on benthic invertebrate communities of filamentous green algal proliferations, the diatom/cyanobacteria guidelines are also recommended for use with filamentous communities where biodiversity is an issue.

8.1.3 Biomass guidelines in relation to maintenance of trout habitat and angling values

The question now arising is whether changes in periphyton community structure and biomass with stream enrichment could affect trout. Whole-stream experiments in North America suggest that enrichment of streams and their periphyton communities can result in a cascade of effects through the food chain to fish. In the oligotrophic Kuparuk River in Alaska, longterm phosphorus addition (to a level below that required to initiate proliferations) has stimulated the whole food-chain, including the production of the Arctic grayling (Peterson et al, 1993). Similarly, Warren et al (1964) fertilised a stream in Oregon with sucrose which increased the biomass of sewage fungus and chironomids, and cutthroat trout production increased two- to tenfold. These results suggest that some nutrient addition to oligotrophic streams can stimulate production up the food chain to the level of fish.

But there is now also extensive evidence to suggest that if enrichment becomes very high it can be detrimental to trout density and biomass. There are common reports from anglers in both New Zealand and in North America that in eutrophic streams draining agriculturally impacted catchments the size and abundance of trout declines, even though total invertebrate density and biomass may increase (J.W. Hayes, pers. comm.). Quinn and Hickey (1990) suggested that as enrichment intensifies, “the loss of ‘behavioural drifting’ stoneflies and mayflies and their replacement by chironomids and algal piercing caddisflies, and net spinning caddisflies and snails (that occur less in the drift than mayflies and stoneflies) would be expected to reduce the feeding efficiency of larger, drift-feeding fish such as adult trout”.

Quinn and Hickey (1990) went on to show that trout biomass increased from oligotrophic streams (<1 percent of their catchment developed for agriculture) to mesotrophic streams (1–30 percent catchment developed), but then reduced greatly (threefold lower) in eutrophic streams (>30 percent catchment developed). Recent studies by Hayes et al (1999) have supported Quinn and Hickey’s hypothesis. Hayes et al (1999) used a trout energetics model to demonstrate that both low drift densities and a shift from large drifting invertebrates such as mayflies and stoneflies to small drifting taxa such as chironomids can significantly reduce the potential maximum size of trout.

In New Zealand we are perhaps seeing a stimulation of fish production with moderate enrichment in two of the most important trout fishing rivers of the South Island, the Motueka and Mataura Rivers. Both these rivers are surrounded by agriculture in their lower reaches and are moderately enriched with periphyton biomass in the range of 10–20 g AFDM/m^2 during periods of low flow (Biggs and Gerbeaux, 1993; Biggs et al, 1996).

This suggests that while a change in invertebrate community composition to a lower proportion of "clean water" and drifting taxa might occur above 5 g AFDM/m^2 (see previous section), relatively short periods of the year with a moderate biomass of up to 20 g AFDM/m^2 dominated by diatoms may be acceptable for the maintenance of trout habitat. Indeed, a review of periphyton data from some of New Zealand's most renowned trout fisheries (Table 13) suggests that good fish populations can be maintained in rivers not withstanding periodically high periphyton biomass.

Table 13: Maximum and geometric mean (~ median) monthly chlorophyll *a* concentrations from some reaches of New Zealand rivers renowned for their trout fisheries. Maximum values are based on transects across reaches and are the highest recorded average transect biomass. Most communities at the time of high biomass were dominated by diatoms (principally *Gomphoneis minuta* var. *cassieae* and *Cymbella kappii*) and filamentous cyanobacteria (principally *Phormidium*).

River	Max. Chlorophyll *a* mg/m2	Mean Chlorophyll *a* mg/m2	Study
Mataura–Gore to Mataura	135[1]		Biggs and Kilroy (unpublished data)
Mataura–Mataura to Wyndham	145[1]		Biggs et al (1996)
Mataura–d/s Wyndham	270[1]		Biggs et al (1996)
Motueka–Woodstock	351	7.0	Biggs (1995)
Motueka–Lower	126	9.5	Biggs (1995)
Riwaka	566	109.4	Biggs (1995)
Tongariro–near Puketarata	125	58	Quinn and Vickers (1992)
Tongariro–near Turangi	95	44	Quinn and Vickers (1992)
Tongariro			
Waiwakaiho	82	15.2	Biggs (1995)

Note: [1] = sampled once during summer low flows.

However, it is also important to recognise that many organisms in streams will be sensitive to not only the magnitude of stress created by factors such as periphyton proliferations, but also the duration of such events. Thus, the length of time that a stream or river contains moderate to high periphyton biomass will also be an important factor to consider in relation to whether high periphyton biomass is likely to have a detrimental effect on fish communities. For example, it could take several months for growth and/or biomass of adult trout to respond to a reduction in the quality of invertebrate food supplies and a change in fish biomass and density may only be recognised when populations become severely stressed. Flow variability, and the associated period of physical stability, will generally determine the duration of stress created by high periphyton biomass. Indeed, while all the rivers listed in Table 13 have periods of high biomass, these periods are usually of only relatively short duration. This is because of a moderate frequency of scouring floods in these rivers (eg, every one to three months) and prolonged periods of low summer flows (ie, longer than three months) usually only occur every five to seven years.

However, it should be recognised that a time could be reached during low flows when the biomass is so high that direct lethal effects may occur on fish through changes in water quality as a result of photosynthetic and respiration activity of the periphyton. For example, degraded conditions with very low night-time dissolved oxygen and high daytime pH have occurred as a result of *Cladophora* dominated proliferations in the Manawatu River. This resulted in fish kills (Quinn and Gilliland, 1989).

Modelling studies have determined that during summer when maximum night-time water temperatures can exceed 21°C, average reach *Cladophora* biomass in the Manawatu River needs to be below 34 g AFDM/m^2 (~120 mg chlorophyll *a*/m^2 for filamentous green algae) so that river dissolved oxygen concentrations do not drop below 5 g/m^3 which could then endanger fish (Quinn and McFarlane, 1989). The periphyton biomass that could result in such degraded water quality in other streams will depend on water temperature, community composition and the reaeration rate of the stream (a function of depth, velocity, bed roughness and temperature).

From the above analysis, it is recommended to place a maximum biomass for the protection of trout habitat at 35 g AFDM/m^2 (~200 mg chlorophyll *a*/m^2 for diatom-dominated communities and 120 mg chlorophyll *a*/m^2 for filamentous algal communities) of sediment surface exposed to light averaged over a reach (a reach most commonly being a run). This is commensurate with the suggested guidelines for aesthetics and contact recreation. It should be stressed that the impacts of such biomass increase strongly with the duration of low flows and when temperatures rise much above 20°C. The 200 mg chlorophyll *a*/m^2 maximum biomass guideline for diatom/cyanobacterial communities is, coincidentally, the same as that suggested by Dodds et al (1998) as a boundary to separate mesotrophic from eutrophic streams based on their chlorophyll frequency distributions.

If rivers are prone to extreme flow reductions, biomass is near the recommended limits for prolonged periods and high temperatures occur, then more restrictive consent conditions developed from modelling studies may need to be invoked as exemplified by the studies for the Manawatu River (Quinn and Gilliland, 1989). Flow variability has been included in the nutrient guidelines (see below) in an effort to incorporate this additional controller of periphyton biomass and ecosystem processes. Considerably more research is required in this area to ensure that these *Guidelines* are generally applicable and thus that habitat conditions are being maintained in areas designated for their fisheries values in relation to section 7(h) of the RMA.

Guidelines to protect angling values need to be depicted in terms of percent cover by filamentous algae. The extent of filamentous algal mats is important to both the aesthetic appreciation of the angling experience and to the amount of fouling of lures and wet flies. In the absence of any other information, the aesthetics/contact recreation guidelines for percent cover of filamentous algae should be adopted.

One further factor that periphyton proliferations appear to influence is the smell of the river and taste of the fish. For example this is an area of complaint by anglers in some rivers in Canterbury during summer (J.W. Hayes, pers. comm.). Some blue-green algae are known to impart muddy and musty flavours to water, and it is possible that this is being transferred into the flesh of trout. Little is currently known about this phenomenon.

8.1.4 Summary of recommended biomass and cover guidelines

A summary of the recommended periphyton biomass and cover guidelines for contact recreation, maintenance of benthic biodiversity, trout habitat and angling is given in Table 14. The percentage cover values apply to the part of the bed that can be seen from the bank during summer low flows (usually <0.75 m deep) or walked on. The biomass guidelines are expressed in terms of reach biomass per unit of exposed substrata (ie, tops and sides of stones) averaged across the full width of the stream or river. Most commonly this will be in a run, but this should be clearly specified in setting consent conditions. For maintenance of benthic biodiversity (ie, a "clean water" benthic fauna), the guidelines are given in terms of mean monthly and maximum chlorophyll *a*. The aesthetics/recreation guidelines are only expected to be applicable over the summer months (1 November – 30 April).

Table 14: Provisional biomass and cover guidelines for periphyton growing in gravel/cobble bed streams for three main instream values.

Instream value/variable	Diatoms/cyanobacteria	Filamentous algae
Aesthetics/recreation (1 November – 30 April)		
Maximum cover of visible stream bed	60 % >0.3 cm thick	30 % >2 cm long
Maximum AFDM (g/m^2)	N/A	35
Maximum chlorophyll *a* (mg/m^2)	N/A	120
Benthic biodiversity		
Mean monthly chlorophyll *a* (mg/m^2)	15	15
Maximum chlorophyll *a* (mg/m^2)	50	50
Trout habitat and angling		
Maximum cover of whole stream bed	N/A	30 % >2 cm long
Maximum AFDM (g/m^2)	35	35
Maximum chlorophyll *a* (mg/m^2)	200	120

8.2 Nutrient concentrations and biomass guidelines

8.2.1 Guidelines for specific instream values

As discussed in Section 4.3.2, linking periphyton biomass to stream nutrient concentrations is very difficult. Table 15 summarises nutrient concentrations predicted to prevent the recommended maximum biomass values of 50 mg chlorophyll *a*/m^2 and 200 mg chlorophyll *a*/m^2 from being exceeded based on various overseas experimental studies with phosphorus limited communities and from studies in New Zealand streams.

Table 15: Maximum soluble inorganic nitrogen (SIN = $NO_3 - N + NO_2 - N + NH_4 - N$) and soluble reactive phosphorus (SRP) supply concentrations (mg/m^3) necessary to prevent maximum periphyton biomass from exceeding the given levels as derived from: 1) experimental studies with phosphorus limited periphyton in the absence of disturbance, and 2) regression equations 1 and 2 (see Section 4.3.3) from nutrient biomass relationships in New Zealand streams with varying lengths of accrual time. The nutrient concentrations in Part II of the table were determined as mean monthly concentrations over a year. Limits of detection are assumed to be around 5 mg/m^3 for SIN and 1 mg/m^3 for SRP if routine analyses are carried out using standard autoanalyser techniques. SIN concentrations in italics were calculated from the limiting SRP concentration assuming an N:P ratio (by weight) for optimum growth in algae of 7.2:1 (Welch, 1992). The chlorophyll *a* at 120 mg/m^2 refers to filamentous green algae dominated communities whereas the chlorophyll *a* at 200 mg/m^2 refers to diatom dominated communities. Chlor. *a* = chlorophyll *a* (mg/m^2); AFDM = ash-free dry mass (g/m^2).

Study	Chlor. *a* = 50		AFDM=35 Chlor. *a* = 120 fil. greens Chlor. *a* = 200 diatoms		Comment
	SIN	SRP	SIN	SRP	
Phosphorus-limited experimental communities					
Horner et al, 1983	*< 20*	< 3	*<70*	<10	*Mougeotia* dominated filamentous green algal communities. Indoor troughs. Mean for velocities >25 cm/s. Estimated from graphs.
Bothwell, 1989	*<7*	<1	*~14*	<2	Diatoms. Outdoor troughs. Estimated from graphs.
Horner et al, 1990	*<7*	<1	*~20–280*	$<3^1$–40^2	Diatom/*Phormidium*/*Mougeotia*; ^{1} = 60 cm/s and ^{2} = 20 cm/s velocity. Indoor troughs. Estimated from graphs.
Walton, 1990	*<7*	<1	*~35*	<5	Diatom/*Phormidium-dominated* communities. Indoor troughs. Estimated from graphs.
N-limited natural stream communities in New Zealand (Biggs, 2000)					
Days of accrual					
20	<20	<1	<295	<26	Based mainly on diatom-dominated communities. Communities mainly N-limited.
30	<10	<1	<75	<6	
40	<10	<1	<34	<2.8	
50	<10	<1	<19	<1.7	
75	<10	<1	<10	<1	
100	<10	<1	<10	<1	

The range of limiting nutrient levels developed from the experiments for accrual times ranging from ~ 20–50 days indicates the degree of uncertainty that still exists in predicting maximum biomass from nutrient supply concentrations. However, there is some reassuringly good agreement between the range of values for diatom dominated communities in the experiments with constant flows (data from Bothwell, 1989 and Walton, 1990) and the limiting nutrient concentrations developed from New Zealand streams for similar accrual periods.

The guidelines derived from Biggs (2000) and listed in the second part of Table 15 are recommended for use in New Zealand because:

- the biomass/nutrient relationships were derived for diatom dominated communities commonly found in New Zealand streams/rivers
- the guidelines take into account some losses due to grazing by invertebrates
- the guidelines have greater flexibility in application to New Zealand streams in that they allow for different flood frequencies and associated duration of the accrual period.

These nutrient concentration *Guidelines* are designed to be mean monthly values for the given average days of accrual. In using the *Guidelines* for developing consent conditions, it is important to recognise that the specific nutrient limiting periphyton growth needs to be identified and consent conditions set in terms of that single, most important, nutrient. It is usually unnecessary to specify conditions in terms of both nitrogen and phosphorus. One of these nutrients will generally be in surplus and, therefore, at much higher concentrations than the guideline shown in Table 15. Also, it is important that the background soluble nutrient concentrations coming into the reach of interest are thoroughly evaluated. This will usually involve monthly sampling for a year to characterise temporal dynamics and get an estimate of the mean concentrations. This will provide the basis for nutrient supply calculations associated with any discharges in relation to the instream management objective and associated guideline biomass.

A note of caution: The nutrient guidelines for the maintenance of benthic biodiversity are very restrictive. These *Guidelines* need to be applied sensibly. It must be remember that the numbers in Table 15 were derived from an empirical model and this contains some error. Further, there will be some situations where mean monthly nutrient concentrations will be marginally exceeded naturally, but excess proliferations of periphyton do not occur (perhaps because of high grazing activity by invertebrates). The nutrient guidelines are there to assist in achieving an instream management objective. It is important not to get bound up in minor breaches of the recommended nutrient levels, but to focus on whether the ISMO is being achieved (ie, focus on ‘outcomes’ rather than ‘inputs’ as measures of success). Thus, when assessing compliance after a consent is issued, also measure the diversity of your invertebrate community to determine if the desired community is being maintained rather than just focusing on nutrients and possible breaches of the guideline values.

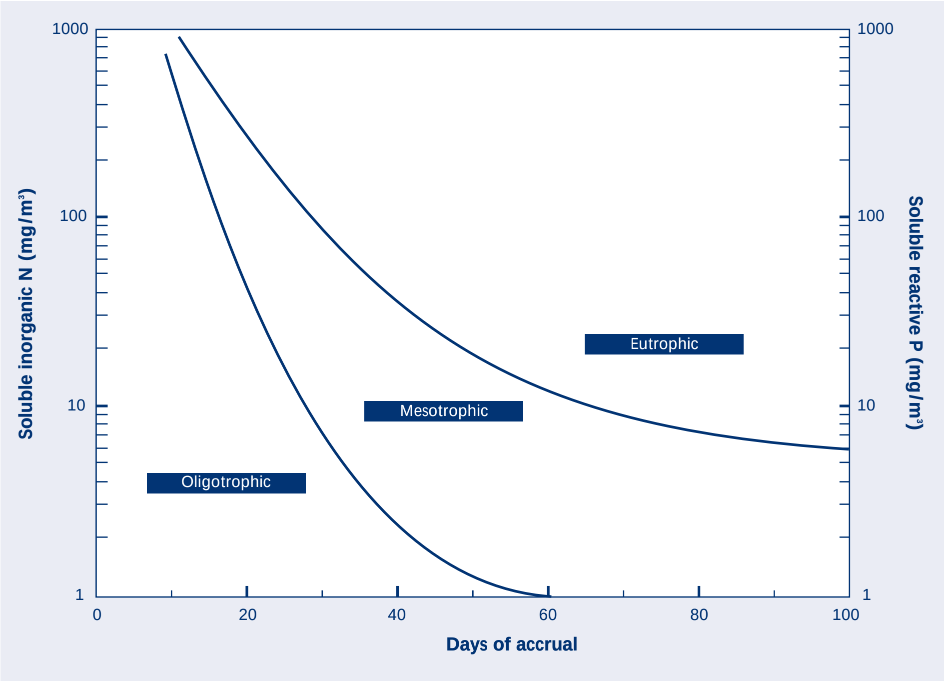
8.2.2 Guidelines for trophic status

There may be some situations where specific values for a waterway have not been identified, so application of a biomass (Table 14), and associated nutrient (Table 15), guideline is inappropriate. As an alternative for general planning and State of the Environment assessments it might be more useful to assess, classify, or predict the general trophic state of the stream/river.

Figure 30 gives a nomograph which depicts maximum chlorophyll *a* bounds of 60mg/m^2 and 200 mg/m^2 to delimit oligotrophic, mesotrophic and eutrophic streams (after Dodds et al. 1998, see Section 7.2) as a function of mean monthly dissolved nutrients for different accrual periods. The oligotrophic - mesotrophic boundary is close to the 50 mg/m^2 maximum chlorophyll *a* limit recommended for the protection of benthic invertebrate biodiversity, whereas the mesotrophic - eutrophic boundary equates to the limit suggested for the protection of aesthetic and trout fishing values.

With this nomograph it is possible to simply read off the likely trophic state for any given mean monthly soluble nitrogen or phosphorus concentration for any expected accrual period. Thus, it could be used to help avoid eutrophic conditions from developing in streams. Also, from the nomograph, it is clear that streams which flood regularly (and thus have short accrual periods) can potentially assimilate much higher levels of nutrients without exceeding the biomass criteria than streams with more benign hydrological conditions (Biggs 2000). This 'sliding scale' approach to setting nutrient criteria should help with developing more realistic management goals for waterways than has been possible previously, and reduce the application of unnecessarily restrictive guidelines.

Figure 30: Nomograph of mean monthly soluble nutrient concentrations that are predicted to result in maximum benthic algal biomass indicative of oligotrophic, mesotrophic, and eutrophic conditions for varying days of accrual ($\underline{d}_{\underline{a}}$) in gravel/cobble-bed streams. The oligotrophic – mesotrophic boundary was set at 60 mg/m^2 chlorophyll a̲ and the mesotrophic – eutrophic boundary was set at 200 mg/m^2 chlorophyll a̲ (after Dodds et al. 1998). These boundaries approximate the maximum biomass criteria adopted for the protection of benthic biodiversity (oligo- to mesotrophic), aesthetics, and trout fishery values (meso- to eutrophic) (see Table 14 page 102) The lines delineating the trophic boundaries were calculated using the soluble inorganic N (SIN) equation on page 43. However, these lines also approximate boundaries for P-limited communities by reference to the right-hand scale, which has been set at 0.1 x the SIN scale, because the mean ratio of biomass from the SIN and soluble reactive P (SRP) models was 10.8. The left-hand (SIN) axis is used for nitrogen limited communities and the right-hand axis (SRP) is used for phosphorus limited communities.



8.3 Mitigation of periphyton proliferations if nutrient control is not possible

In many situations such as in streams draining nutrient rich basement rock and where significant groundwater seepage occurs, it is not feasible to control nutrient inputs. In such situations riparian shading, the maintenance of a clean gravel/cobble substrata that is relatively stable to enhance invertebrate grazer densities, and maintaining high water velocities offers the best possibility for reducing accumulations of filamentous green algae.

Recent research in New Zealand and North America has indicated that periphyton proliferations can be controlled if light levels over summer are reduced by at least 60 percent (and probably nearer 90 percent) with riparian shade (Quinn et al, 1997b; Rier and Stevenson, pers. comm.). It appears that at a certain degree of cover there may also be a change from a filamentous algae dominated community to one dominated by diatoms. However, the threshold for this change has not been clearly defined. This control measure will be most useful in smaller streams. Recently, Davies-Colley and Quinn (1998) surveyed many sites in five regions of the North Island and found that periphyton biomass of >100–150 mg chlorophyll *a*/m^2 mainly occurred where light levels exceeded 3 percent of unobstructed sky light. Light levels of $\leq$3 percent were achievable with bank-full stream widths of $\leq$4.5 m if riparian zones were covered in native forest species and $\leq$5.5 m if riparian zones were covered in tall pine trees. These stream widths provide a useful guide below which riparian planting could control periphyton proliferations.

Invertebrate grazers may have a major controlling influence on periphyton biomass if the densities of the large grazing taxa such as caddisflies and snails can be maintained at a high level. Welch et al (1992) carried out a summer survey of periphyton and invertebrates above and below inorganic waste discharges in seven New Zealand streams. Although nutrient concentrations were very high, it appeared that proliferations of periphyton only occurred where grazer densities were <3000/m^2. Experiments with different densities of mayflies and caddisflies, and adult snails largely supported the stream survey results (Welch et al, 1999). However, periphyton growth rates in the experiments were not high and whether such grazer densities are able to control periphyton in very enriched habitats is still unknown. Probably one of the critical issues in this is whether the habitat is stable for sufficiently long so as to allow the grazer numbers to build up to densities that can keep up with high rates of primary production. It is clear that invertebrates can prevent local enrichment from creating periphyton proliferations through an increase in densities (Biggs and Lowe, 1994) and it is possible that such adjustments could occur over whole stream reaches if a high quality, stable invertebrate habitat is maintained.

Finally, high water velocities can also prevent thick periphyton accumulations. Recent studies have suggested that communities dominated by filamentous algae can be maintained at a biomass of <100 mg chlorophyll *a*/m^2 if near-bed velocities are >0.3 m/s (Biggs et al, 1998a). At such velocities, the drag on the filaments become too great for either the holdfast or the inter-cellular connections and portions of the mat slough. Situations where it may be possible to control velocity are where rivers are regulated for, say, summer storage of water or where major abstractions are occurring for irrigation. In such situations suitable control of the excess growths may be achieved by short-term (say 1–2 h) releases of high flows (eg, >5X the residual flow). Biggs and Thomsen (1995) found that periphyton were sloughed very quickly as velocities are increased significantly above what the community is acclimated to and that for filamentous communities velocities may only need to be 3–6 times higher to achieve significant control (also see Biggs and Close, 1989). However, it is likely that such control measures would need to be repeated at regular intervals (say, every 2–4 weeks) because of community regeneration.

9 References

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Appendix I: Glossary

Algae

Simple chlorophyll-bearing cells. Most are aquatic and unicellular. Some may link to form colonies or filaments and become macroscopic. An evolutionary early form of plants. Singular: alga.

Autotrophic production

A process of building organic matter from inorganic matter such as carbon dioxide and nitrogen using light energy to power the process.

Benthic invertebrates

Bottom-dwelling animals without backbones in streams (eg, snails, worms, caddisflies, mayflies)

Biomass

The weight of living matter of an alga, plant or animal. For stream periphyton, this weight is usually expressed in terms of ash-free dry weight or chlorophyll *a* on an aerial basis.

Biota

Any assemblage of living organisms in a specific area.

Chlorophyll

Pigment in algae and plants responsible for capturing energy from light to drive metabolic processes and the synthesis of organic matter from inorganic substances (see autotrophic production).

Community

An assemblage of different species belonging to the same general group of organisms.

Competitive (taxa)

Species which have the ability (traits) to be superior at capturing resources (eg, nutrients and light) in a niche or site and therefore come to dominate or form most of the biomass after prolonged periods without disturbance (eg, *Cladophora*, *Spirogyra*). Such species are usually slow to colonise and relatively slow growing, but which form big structures, overtopping the smaller species that may invade a site quickly and reproduce fast (pioneer species).

Cyanobacteria

Filamentous bacteria containing chlorophyll and capable of full autotrophy. Previously grouped with the algae, but now recognised as a distinct group of prokaryotic organisms (not containing distinct organelles) more closely related to bacteria. They are one of the most primitive groups of organisms.

Diatoms

Large subgroup of algae containing a specific set of pigments and an internal silica shell (frustule).

Disturbance

Punctuated loss of biomass (or death) of populations/communities at time-scales much shorter than the time required for regeneration of the biota.

Ecosystems

The combined grouping of biota and their habitats, including functional and structural components.

Epiphytic

Living on the surface of another plant or alga.

Flagella

Thread-like appendages attached to the exterior of a zoospore that flap to propel the zoospore (reproductive, motile, spore).

Food chain

The transfer of food or energy from plants to grazing animals to predatory animals.

Freshet

A small flood that might occur many times a year and not result in significant bed sediment movement (eg, <50% of the bed moving).

Frustule

Intricately sculptured internal wall (in two halves) of a diatom made of silica. The pattern of sculpturing is important in diatom identification.

Genera

A grouping of homogeneous species that are very closely related (first level of aggregation in a hierarchical taxonomic classification of organisms). Singular: genus.

Holdfast

A specialised cell at the based of a filament that is flexible in shape to lock into pits on the surface of stones enabling attachment of the alga.

Macrophytes

Larger, multi-celled, aquatic plants (eg, >10 cm) with differentiation of tissue to form distinct stems and leaves/pinnules. Includes mosses, liverworts and true vascular aquatic plants such as oxygen weed and *Typha*.

Mass transfer

The process of transfer and uptake of essential nutrients to biota (periphyton), usually measured in terms of mass of a mineral taken up per unit of time per unit area of stream bed.

Metabolites

A general term to describe the products of metabolic processes.

Motile

Capable of self-propulsion or spontaneous movement.

Niche

Specific sector of a habitat for which certain taxa have developed specialised adaptations to exploit.

Nutrients

Organic or inorganic chemicals needed by organisms for growth and reproduction.

Periphyton

A group of organisms in aquatic environments specialised to live on and exploit much larger (usually inert) surfaces. Groups of organisms include fungi, bacteria, protozoa, and algae. The most conspicuous group is the algae and this group is usually the focus of most studies of periphyton.

Photosynthesis

The process where starches and sugars are produced within plant (or plant-like) cells using carbon dioxide, inorganic nutrients and sunlight. Sunlight is captured with the chlorophyll molecules.

Phylogenetic

Evolutionary linkages of an organism that are encompassed in its hierarchical classification.

Phytoplankton

Algae, usually single celled, that are free-floating in the water.

Pioneer

Taxa that are the first to colonise and exploit bare areas of habitat after a space clearing disturbance. These taxa are characterised by having fast rates of immigration and/or high resistance to disturbance, and fast rates of reproduction/high capacity for seeding.

Population

Many individuals of one species.

Primary producers

A general term describing any organisms capable of synthesising organic matter from inorganic minerals and sunlight.

Proximate variables

Factors in the environment that directly control the distribution, growth and reproduction of organisms (eg, phosphorus, temperature, water velocity, sediment movement).

Raphe

A pair of slits on the surface of a diatom frustule through which cytoplasmic material can pass (allowing movement of the cell).

Refugia

A place where organisms can escape predation or the effects of an agent of disturbance.

Sewage fungus

Filamentous bacteria (predominantly *Sphaerotilus*) that proliferate when there are high concentrations of low molecular weight (dissolved) organic matter such as sucrose in the water. They form mats that look like cotton-wool under water. Sometimes they have a pinkish colouration on the outside.

Slough(ing)

Scouring or peeling of a periphyton mat off its substrate.

Species

Taxa that can only interbreed with each other (ie, reproductively isolated)

Taxa/taxon

A group of taxonomically related individuals (eg, a group of species that belong to the same genera or family). Taxon (singular) is used when referring to what is probably one species, but the species designation/name is not known.

Trichome

Filament of a cyanobacterium that often contains heterocysts (nitrogen fixing bodies).

Trophic (levels)

A system of classifying organisms according to what they feed on. Most commonly this term is used to refer to different levels of the food chain.

Ultimate variables

Broad-scale controllers of ecosystem processes such as climate and geology which provide general constraints on the variability or level of expression of proximate variables.

Water quality

The chemical and physical attributes of water such as turbidity, phosphorus concentrations, temperature and major ion concentrations.

About the Ministry for the Environment

Our mission - Making a difference through environmental leadership

The Ministry for the Environment is working to achieve effective management of the New Zealand environment. That includes reporting to the Government on the state of our environment and the way that environmental laws and policies work in practice. It also includes developing proposals and tools for improving environmental management. Councils, particularly regional councils, deal with most day-to-day environmental management.

We are responsible for government policies covering:

- management
- air and water quality
- hazardous substances and contaminated sites of the ozone layer change.

We provide an environmental viewpoint on government policies such as Treaty of Waitangi settlements, and the energy sector and transport sector reforms. We work with other government agencies on matters where we do not have the main responsibility, such as biological diversity, marine environmental issues and the relationship between trade and environmental issues.

We know that aspects of our work are important to councils, iwi, businesses, professional and environmental organisations and many others in the community. We want to understand their concerns and how any changes in policy or laws will affect them. Our work, therefore, includes a strong element of consultation with those interested in environmental policy, both through submissions on proposals and through regular information meetings with key groups. We seek to provide the information and advice that councils, businesses and the wider community need to make environmental policy work in practice.

The Ministry acts on behalf of the Minister for the Environment in carrying out his duties under the Resource Management Act 1991. This includes reporting to him about local government performance on environmental matters. We will also report on the work of the new Environmental Risk Management Authority.

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