NIWA
Taihoro Nukurangi

Review of the New Zealand instream plant and nutrient guidelines and development of an extended decision making framework: Phases 1 and 2 final report

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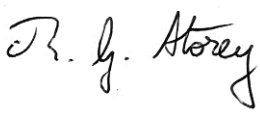

Richard Storey

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Executive summary

Aquatic plants are a natural component of stream and river systems. However, abundant growth of instream plants is sometimes problematic, impacting upon human and ecological values. The magnitude and nature of instream plant growth is controlled by a number of physicochemical and biological factors including light and nutrient availability, flow and substrate characteristics, temperature, the availability of nuisance colonist species, and herbivory.

The overall aim of this Envirolink Tools project was to develop a decision-making/risk assessment framework that would allow Regional Councils to define appropriate instream plant abundances and defensible dissolved nutrient (N & P) concentrations as water quality standards for a broad range of river types and hydrological regimes. The work was intended to supplement and clarify existing national guidelines and be based on a modelling approach calibrated using all suitable national data. The project consists of three phases. This report summarises work towards the first two contracted objectives in phases 1 and 2 which were to: (1) undertake a literature review, compile and analyse national data and develop a preliminary framework, and (2) present this framework at a workshop and formulate a collaborative plan to fill critical data gaps and progress the development of this tool in phase 3.

Within the first two phases of this project a review of the national and international literature and an analysis of the existing National Rivers Water Quality Network (NRWQN) database were used to develop several new instream plant abundance guidelines, regression models for periphyton cover, and two generally applicable Bayesian Belief Networks (BBNs) to predict the probability of nuisance filamentous periphyton and macrophyte growths in streams/rivers. The BBNs can incorporate multiple influences and information from a variety of sources including empirical data, various types of models, literature information and expert opinion and were considered the most appropriate modelling approach to use to develop a preliminary general framework applicable across multiple river types. National and regional scale testing of the developed models indicated that they correctly predict the risk of nuisance plant abundance at most sites. Two decision support trees were also developed to guide the process of nutrient limit setting to prevent the occurrence of instream nuisance plant growths. The decision support trees incorporated the BBNs and other existing tools. A project workshop was held on the 22 November 2011 in Wellington and the suggestions arising from the workshop have been incorporated into this report.

The new instream plant abundance guidelines developed in this report are as follows:

- A provisional guideline of ≤50% of macrophyte channel cross-sectional area or volume (CAV) is recommended to protect instream ecological condition, flow conveyance and recreation values.
- A provisional guideline of ≤50% of macrophyte channel water surface area (SA) is recommended to protect instream aesthetic and recreation values.
- A periphyton weighted composite cover (PeriWCC) can be calculated as %filamentous cover + (%mat cover/2) with an aesthetic nuisance guideline of ≥30%.

- Provisional general guidelines of <20%, 20-39%, 40-55% and >55% periphyton weighted composite cover are recommended as indicators of ‘excellent’, ‘good’, ‘fair’ and ‘poor’ ecological condition, respectively, at sites where other stressors are minimal.

Information compiled for this report has also clarified the following aspects of the existing national guidelines.

- Data used to derive the *New Zealand Periphyton Guideline* calculated accrual period using whole-year (not summer) mean daily flow data, a flow record that corresponded to matched periphyton and nutrient measurements, a flood defined as three times the median flow and no flood interval filter period.

- An analysis using the River Environment Classification database has confirmed that sites used to derive the *New Zealand Periphyton Guideline* were a good representation of hill-fed, cobble bed New Zealand rivers. Other river types were not well represented and these are considered to comprise ca. 30% of all New Zealand river segments.

The final section of the report includes a proposed structure and tasks for development of the Phase 3 refined framework and guidance document.

1 Introduction

1.1 The nuisance plant problem

Aquatic plants are a natural component of the biodiversity and functioning of stream and river systems and contribute to ecosystem services such as carbon fixation, nutrient cycling and sequestration, and biohabitat formation that support broader biodiversity. However, over-abundance of growth of instream plants can sometimes become a nuisance to river values when it:

- hinders contact recreational use (e.g., for swimming, boating, angling)
- reduces aesthetic quality
- restricts land drainage, by impeding downstream conveyance of flow via reducing effective channel volume and increasing channel roughness
- clogs intakes for water supply and/or power generation, and
- reduces ecological habitat quality (e.g., depletes dissolved oxygen (DO) and/or alters pH for invertebrates and fish, smothers substrate and increases deposited sediment).

In this document we focus mainly on periphyton and macrophytes as these are the plant forms that most commonly form nuisance growths in New Zealand's wadeable streams and rivers. While both native and introduced plant species can grow luxuriantly when conditions are suitable, for macrophytes, it is usually introduced species that are considered most problematic. We also briefly discuss phytoplankton and cyanobacteria, and the invasive freshwater diatom, *Didymosphenia geminata* (didymo).

The relationship between nuisance plant abundance and nutrient concentrations in rivers is complex due to:

- feed-backs between nutrients and plant biomass/growth (i.e., instream plants need nutrients to grow but this growth reduces ambient the nutrient concentrations in the water column, so that nutrient/biomass relationships are not straight-forward)
- the limiting nutrient (nitrogen (N) vs. phosphorus (P)) differing among streams, depending on whether the other is available at saturating levels (but note that the form of nutrient limitation can vary spatially and temporally within a river system and that is usually wise to manage both N and P (Wilcock et al. 2007))
- the wide range of potential nuisance plant species that differ in nutrient requirements and other environmental optima
- other river environmental characteristics that influence plant growth (light reaching the streambed, flow variability, temperature, substrate type, invertebrate grazing)
- availability of invasive macrophyte propagule and colony forming algal material

- human values (e.g., biodiversity, aesthetics, flow conveyance) potentially differing in their nuisance abundance thresholds.

The feedback between nutrients and benthic (bed) plant abundance makes nutrient guideline definition particularly problematic in rivers. Plant growth (and associated habitat change) removes nutrients from the flowing water column into plant tissue and can also create conditions that enhance nitrogen removal by denitrification (e.g., macrophytes often promote development of carbon-rich sediment mounds and carbon-rich oxic-anoxic interfaces can develop within thick periphyton mats). Furthermore, diffuse nutrient inputs to rivers are often least during periods when other conditions are most favourable for instream plant growth (e.g., steady flow, high light and temperature). Thus, *instantaneous* plant abundance and nutrient concentrations at a site are often negatively correlated, while correlations are positive between annual or summer *average* concentrations and average or annual maximum abundance amongst different sites.

These complexities make the search for relationships between nutrients and riverine nuisance plant thresholds akin to “hunting the snark” (Lewis Carroll’s 1874 poem describing "the impossible voyage of an improbable crew to find an inconceivable creature"). In this report we address this challenge by discussing different instream plant thresholds for nuisance effects on various values and presenting a framework that accounts for multiple influences on nuisance plant abundance using Bayesian Belief Networks (Reckhow 2003) and multi-factor regression models that predict the likelihood of nuisance plant growths developing.

1.2 Contract & objectives

The overall aim of this Envirolink Tools project is to “develop a decision-making framework which will allow councils throughout New Zealand to define defendable dissolved macronutrient concentrations (phosphorus, P; nitrogen, N) and instream plant abundances as water quality standards for a broad range of river types and hydrological regimes”. The work is to be based on a risk-assessment model calibrated using all data available nationally. The project has three phases, the first two of which are covered by this report.

The contracted objectives are:

Phase 1: Undertake a literature review, compile and analyse national data and develop a preliminary decision-making framework and discussion document by 30 June 2011.

Phase 2: Hold a workshop to review the preliminary decision-making framework and develop a collaborative plan with Regional Councils to fill any critical data gaps for future refinement of the framework by 30 June 2012.

Phase 3: (not currently funded). Critical data gaps filled and further refinement of the framework.

Note that phase 3 is required to fulfil the project’s overall aim. Planning for this phase of the project is dependent on the outcomes of phases 1 and 2.

1.3 Overview of factors regulating nuisance plant growth

The magnitude and nature of instream plant growth is controlled by many factors including light and nutrient availability, flow and substrate characteristics, colonist availability and herbivory. Like their terrestrial counterparts, aquatic plants require sunlight and nutrients to grow. These are primary factors affecting their growth. Plants also require inorganic carbon (CO_2 and HCO_3^-) as well as trace elements but these are usually regarded as being available in adequate amounts. Water velocity and flood frequency are important factors, with attached species vulnerable to scour during floods and some species unable to establish at all in swift-flowing waters. Water, and the substances contained within it, can also attenuate sunlight, so stream water depth, clarity and composition will regulate the growth of submerged plants. Temperature also affects instream plant growth and its nuisance effect. Over the natural temperature ranges encountered in most New Zealand streams and rivers, plant growth rates generally increase in response to higher temperatures. Higher temperatures can also exacerbate DO depletion as a result of plant metabolism. Just like land plants, aquatic plants can be consumed and their abundance regulated by herbivorous biota. Aquatic insects, waterfowl and fish are the main consumers of plants in streams and rivers. While not generally considered a major regulator of instream plant abundance in New Zealand waterways, there may be instances where a high density of grazers could control the development of nuisance biomass.

1.4 Summary of existing national guidelines

1.4.1 MfE Water Quality Guidelines No. 1

In 1992, the Ministry for the Environment (MfE) released a set of guidelines for the control of undesirable biological growths in water (MfE 1992). These guidelines included nuisance plants (phytoplankton, benthic algae (periphyton) and macrophytes) and were provided for different waterbody types including lakes, rivers/streams and estuaries. The recommended guidelines for periphyton and macrophytes relevant to rivers and streams are provided below.

Periphyton

Biomass guidelines:

"*To protect contact recreation, the seasonal maximum cover of stream or river beds by periphyton as filamentous growths or mats (>ca. 3mm thick) should not exceed 40 percent, and/or biomass should not exceed 100 mg chlorophyll* a *m^{-2} or 40 g AFDW m^{-2} of exposed surface area". (N.B. this guideline is provisional – rigorous investigations of human perceptions of changes in aesthetics and recreational value of water due to periphyton are required)*."

"*There are insufficient data to allow recommendation of periphyton biomass criteria for protection of other water use classes. Biomass limits for maintenance of adequate dissolved oxygen and pH must be site-specific (e.g., taking into account the site's air/water/gas transfer rate and pH buffering capacity). Research is required to develop models of the effects of nutrients and other factors on periphyton growth and metabolism.*"

Nutrient guidelines:

"*The limited available data indicate that the concentration of dissolved reactive phosphorus (DRP) needs to be below approximately 15-30 mg* m^{-3} *or the concentration of dissolved inorganic nitrogen (DIN=*NO_3*-N+*NH_4*-N) needs to be below approximately 40-100 mg* m^{-3} *for nutrients to have any significant effect on periphyton biomass in flowing waters. If either nutrient occurs at lower concentrations, periphyton biomass yield is expected to decline. Blanket imposition of nutrient limits to prevent undesirable periphyton growth is not recommended, because a number of other factors have strong influences and should be considered on a site-specific basis.*"

Macrophytes

Biomass guidelines:

"*There are insufficient data to provide a basis for macrophyte biomass guidelines for protection of use of water bodies for contact recreation and general aesthetic purposes. Such guidelines are expected to vary with the water body type. For example, in clay-bedded, lowland streams 50 percent cover of the stream bed by macrophytes may be natural and aesthetically acceptable, whereas this would probably be unacceptable in a gravel-bedded, upland stream or river*."

"*Site-specific biomass guidelines are necessary for undesirable macrophyte growths in relation to the maintenance of adequate DO and pH, for recreation and aesthetics in lakes, and for control of nuisance effects in water intakes and land drainage. Research is required to evaluate the applicability to New Zealand conditions of existing models for macrophyte growth and effects of macrophyte metabolism on water quality in rivers*."

"*There are insufficient data available to provide a basis for recommendation of macrophyte biomass guidelines for protection of water use for the purposes of irrigation, industrial abstraction and water supply*."

Nutrient guidelines:

"*Nutrient controls are not considered to be generally appropriate for control of macrophyte biomass in ecosystems where plants are exposed to low levels of physical disturbance (e.g., most lakes and spring-fed streams). In such systems, increases in nutrients may reduce macrophyte biomass by increasing phytoplankton biomass and hence shading of macrophytes. Nutrient guidelines are appropriate for control of macrophyte biomass in streams where cycles of growth and die-back occur due to other factors. In these situations, high nutrient concentrations may increase the biomass attained between disturbances, and the duration of periods of high biomass, by increasing macrophyte growth rates. However, at present, there are not sufficient data available to allow recommendation of nutrient concentrations to limit macrophyte growth in such situations*."

1.4.2 MfE New Zealand Periphyton Guideline

In 2000, the Ministry for the Environment released the *New Zealand Periphyton Guideline* (MfE 2000). Within the document a set of provisional guidelines is provided "…*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 for periphyton growing in gravel/cobble bed streams for three main instream values are as follows (Table 1-1):

Table 1-1: *New Zealand Periphyton Guideline* recommended periphyton abundance guidelines.

Instream value/variable	Diatoms/cyanobacteria	Filamentous algae
Aesthetics/recreation		
(1 November to 30 April)		
Maximum cover of visible stream bed	60% >0.3 cm thick	30% >2cm long
Maximum AFDM (g m^{-2})	N/A	35
Maximum chl *a* (mg m^{-2})	N/A	120
Benthic biodiversity		
Mean monthly chl *a* (mg m^{-2})	15	15
Maximum chl *a* (mg m^{-2})	50	50
Trout habitat and angling		
Maximum cover of whole stream bed	N/A	30% >2cm long
Maximum AFDM (g m^{-2})	35	35
Maximum chl *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 substrate (i.e., 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.*"

The nutrient guidelines (mean monthly concentrations over a year) to ensure that peak periphyton biomass does not exceed the biomass guidelines are as follows (Table 1-2):

Table 1-2: *New Zealand Periphyton Guideline* recommended nutrient concentrations to ensure that peak periphyton biomass does not exceed biomass guidelines.

Study	Chl *a* = 50 mg m^{-2}		AFDM = 35 g m^{-2} Chl *a* = 120 mg m^{-2} (filamentous) Chl *a* = 200 mg m^{-2} (diatom)	
Days of accrual	SIN mg m^{-3}	SRP mg m^{-3}	SIN mg m^{-3}	SRP mg m^{-3}
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

SIN=soluble inorganic N (equivalent to dissolved inorganic N).

SRP=soluble reactive P (equivalent to dissolved reactive P).

"*In using the soluble 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.*"

1.4.3 ANZECC guidelines

The latest ANZECC guidelines (ANZECC 2000) provide default low-risk trigger values for nutrients, dissolved oxygen/pH and clarity/turbidity in slightly disturbed New Zealand river ecosystems to assess potential risk of adverse effects (which include nuisance aquatic plant growth) (Table 1-3). These are derived from 80th or 20th percentiles (as appropriate for the attribute) in available regional reference datasets (Davies-Colley 2000) – hence they are not "effects-based" in terms of effects on nuisance periphyton occurrence but instead reflect the range limits of natural concentrations of parameters at reference sites. If these default low-risk trigger values are exceeded then further site-specific investigations may be warranted. The guidelines also stress that the preferred approach to determine low-risk trigger values is for territorial authorities to develop site-specific guidelines using biological effects data, comparison with local reference conditions and/or considering effects of ecosystem-specific modifying factors.

Table 1-3: ANZECC default low-risk trigger guidelines for selected variables in New Zealand rivers.

Ecosystem type	TP	DRP	TN	NO_x	NH_4	DO (% saturation)		pH [c]		Clarity [d]	Turb.
			mg m^{-3}			Lower limit	Upper limit	Lower limit	Upper limit	m	NTU
Upland river	26 [a]	9 [a]	295 [a]	167 [a]	10 [a]	99	103	7.3	8.0	0.8 [e]	4.1 [e]
Lowland river	33 [b]	10 [b]	614 [b]	444 [b]	21 [b]	98	105	7.2	7.8	0.6	5.6

[a] values for glacial and lake-fed sites in upland rivers are lower.

[b] values are lower for Haast River which receives waters from alpine regions.

[c] DO and pH percentiles may not be very useful as trigger values because of diurnal and seasonal variation – values listed are for daytime sampling.

[d] measured by black disk or Secchi disk.

[e] clarity and turbidity values for glacial sites in upland rivers are lower and higher respectively.

[f] NO_X and NH_4 guidelines are for N (i.e., NO_X-N and NH_4-N).

1.5 Limitations of existing national guidelines

A number of specific, critical limitations have been identified with the existing New Zealand guidelines. These are discussed below:

1.5.1 No macrophyte guidelines

There are currently no national macrophyte abundance or nutrient guidelines for macrophytes in rivers and streams. This issue was identified in the *MfE Water Quality Guidelines* (MfE 1992). At the time it was considered that there was insufficient data to recommend any guidelines. Twenty years has now elapsed and it is considered that more data and information could now be available to revisit this issue.

1.5.2 No periphyton composite cover guideline

The New Zealand Periphyton Guideline (MfE 2000) provides separate filamentous and mat cover thresholds for periphyton. Similarly the earlier *MfE Water Quality Guidelines* (MfE 1992) suggested as a provisional guideline that seasonal maximum cover of filamentous algae *or* mats should not exceed 40%. However, there may be instances where cover by both periphyton forms is moderately high but not above current thresholds, whereas the combined cover of these two nuisance growth forms comprises a very high proportion of the river bed. For example a 30% cover of thick algal mats combined with a 30% cover of filamentous algae. Provision of an unambiguous combined cover threshold is needed.

1.5.3 No periphyton cover guideline for ecological impact

Many Regional Councils, and the National Rivers Water Quality Network, measure periphyton *cover* as opposed to periphyton *biomass* (as chlorophyll *a* and ash-free dry matter (AFDM)); the latter is more time-consuming and expensive to measure and there are difficulties in ensuring a representative sample is collected. *The New Zealand Periphyton Guideline* provides a chlorophyll *a* (biomass) threshold to protect benthic biodiversity but development of an equivalent cover threshold, or a means to convert chlorophyll *a* to cover and vice versa, would be useful.

1.5.4 Benthic biodiversity guideline needs further evaluation

The benthic biodiversity guideline in the *New Zealand Periphyton Guideline* was derived from a relatively limited analysis, primarily based on a plot of periphyton AFDM versus macroinvertebrate %EPT (paired data for 31 sites in 21 streams). Further evaluation of this guideline is warranted and should include examination of relationships between periphyton abundance (as cover and chl *a*) and a range of macroinvertebrate community indices.

1.5.5 Accrual period is not defined

Accrual period calculation is required when using the *New Zealand Periphyton Guideline* and has a strong influence on the derived nutrient guideline values for N and P. Publications cited in the *New Zealand Periphyton Guideline* use a FRE3 hydraulic calculation for determining accrual periods, however, they either do not specify the “interflood filter period” or use variable filter periods after an initial flow event during which subsequent events are not counted. The filter period is the minimum interval between counting of significant floods. In Biggs (2000) accrual time in days was calculated as 365/FRE3 during the period of data collection. Whether instantaneous or daily average flow was used and a filter period between floods was not specified. Standardisation is required to improve the defensibility of the *New Zealand Periphyton Guideline* for generic and site-specific applications.

1.5.6 Nutrient thresholds applicable to certain river types

The model that the *New Zealand Periphyton Guideline* used to derive nutrient thresholds is based on predictions of periphyton chl *a* from measurements of biomass accrual time and nutrient concentrations. Data for the model were derived primarily from gravel/cobble bed rivers. The model does not take into account other potentially important regulators of periphyton growth in other river types, in particular availability of light and stable attachment substrates. This makes it difficult to apply the model to other river types (particularly streams with soft substrates, riparian shading and/or low water clarity). The nutrient thresholds in the *New Zealand Periphyton Guideline* are essentially a “worst-case scenario”, applicable to streams where all regulators other than nutrients and flow are optimal (i.e., no shading, high water clarity, gravel-cobble substrates) and, if applied in other situations, are likely to be conservative. The *New Zealand Periphyton Guideline* acknowledges that the nutrient guidelines are very restrictive and cautions that they need to be applied sensibly. Further guidance as to when these nutrient guidelines are appropriate to use is needed and alternative approaches developed for situations when they are not.

2 Overview of methods

2.1 Literature review

The national and international literature was searched for reports and journal articles on instream plant and nutrient guidelines/criteria and on relationships between instream plant abundance and related physicochemical and biological variables. We used this literature review primarily to develop provisional instream macrophyte nuisance abundance guidelines (see Section 3) and to inform development of general nuisance periphyton and macrophyte Bayesian Belief Network (BBN) models (see Section 2.4).

2.2 Regional Council data

A request and guidance for data collection for this project was made in December 2009 (see Appendix A). The project began in July 2010 and Regional Councils were approached in November 2010 to provide the data requested. These data were supplied and collated in the period from December 2010 to May 2011. Unfortunately, lack of data for some parameters and differences in methods and reporting approaches between regions for other parameters meant that the data supplied could not be collated and interrogated as a single database for this project. Several Regional Councils did not supply any data at all (See Section 7.3 for further details).

2.3 National Rivers data

The National Rivers Water Quality Network (NRWQN, 77 sites in 48 rivers, Davies-Colley et al. 2011) holds the largest, long-term, New Zealand dataset on periphyton cover and related environmental variables (i.e., Quinn and Raaphorst 2009). This dataset was used to examine relationships between periphyton cover and related physicochemical and biological variables using regression and graphical approaches. Further details of the analysis are provided in Section 6. Note that the NRWQN is characterised by a large proportion of large and relatively unpolluted rivers. Where possible, sites in the NRWQN were selected to have median flow >1m^3 s^{-1} (Smith and McBride 1990) and these range from 2-260 m^3 s^{-1}, with a median of 26.9 m^3 s^{-1}, (Maasdam and Smith 1994), so that they represent mainly larger New Zealand rivers. Regional Council datasets were therefore considered likely to better represent the broad range of river/stream types across New Zealand.

2.4 BBN Modelling

BBN models were used to summarise the available literature and findings from the NRWQN periphyton analysis on factors influencing the risk of nuisance instream plant abundance in a wide range of river/stream systems. We considered that the BBN approach was the most appropriate method to use in this project because of data limitations and the need for development of a broad framework that could encompass diverse river types. BBNs are particularly useful for this purpose because they can incorporate multiple influences, and can include information from a variety of sources including empirical data, various types of models, literature information and expert opinion (Reckhow 2003, Giles 2008) (see Table 2-1 for overview of alternative approaches). BBN model development is described further in Section 7.

Table 2-1: Approaches for deriving nutrient guidelines.

Approach	Description	Advantages	Limitations	Examples
Mechanistic process models	Establish algal growth relationships with key driving variables (including: hydrodynamics, sediments, nutrients, shade, temperature).	Site-specific can deal with downstream nutrient attenuation; can give continuous predictions in time and space.	Costly, data intensive. Limited broad-scale applications.	Great Lakes Cladophora models (e.g., Auer & Canale 1980, 1982). Rutherford models (Rutherford et al. 2000, Rutherford 2011).
Regression models	Regression relationships between laboratory and field algal populations and a limited suite of predictors.	Fixed point predictions (Means, Annual maximums). (Usually bi-variate or trivariate e.g., Periphyton vs N and /or P). Can be used with quantile regression approach.	Need to determine limiting nutrient. Deterministic approach provides little information on spatial/temporal variability.	MfE (2000); Biggs (2000), Dodds et al. (1997).
Probabilistic approaches	Probabilistic predictions (usually bi-variate or trivariate e.g., Periphyton vs N and /or P).	Can be used with quantile regression approach.	Need lots of data.	Downing et al. (2001).
Reference benchmarks	Using natural or least-disturbed sites to assess condition of others using classifications based on natural environmental settings or models that use continuously variable environmental attributes as inputs (Hawkins et al. 2010).	Simple but conservative.	Not effects-based. Need to adequately match reference and monitoring water bodies. Arbitrary threshold for triggering of "effect".	ANZECC (2000).
Bayesian Belief Networks	A Bayesian network consists of a graphical structure and a probabilistic description of the relationships among variables in a system.	Integrative approach. Predict risk of annual nuisance levels with multiple influences. Can be used with quantile regression approach. Prior probabilities can be updated as more information becomes available. Can include both empirical data and expert opinion.	Does not predict site dynamics. No single nutrient guideline values produced.	This study. Borsuk et al. (2004).

2.5 Project workshop

A project workshop was held on the 22 November 2011 at the Greater Wellington Regional Council offices. A discussion document was circulated prior to the workshop that outlined the necessary background information and preliminary framework that had been developed. The key components of this document were subsequently presented and discussed at the workshop. Recommendations arising from the workshop were incorporated into this report.

3 Macrophyte abundance guidelines

Section summary:

- There are currently no national nuisance macrophyte abundance guidelines or protocols for macrophyte measurement available for streams and rivers but a need for these has been identified.
- Macrophyte abundance in streams and rivers should be quantified as a proportion of channel cross-sectional area or volume (CAV) and water surface area (SA) as these are the best indicators of nuisance effect. A suggested protocol for undertaking these measurements is provided in this report.
- A provisional guideline of ≤50% of channel CAV is recommended to protect instream ecological condition, flow conveyance and recreation values.
- A provisional guideline of ≤50% of channel water SA is recommended to protect instream aesthetic and recreation values.
- Research linking macrophyte abundance levels to effects on key instream values is required to refine these provisional guidelines.

3.1 Introduction

Nuisance growths of aquatic macrophytes are generally most common in open (unshaded), nutrient-rich lowland streams (Haslam 1978) and it is in such situations that the application of nuisance abundance thresholds will most likely be applied. However, they can also occur in spring-fed upland streams (ECan 2011). A study in the US Northwest showed that nuisance macrophyte growths were most extensive in waterbodies where the surrounding land area was near a population centre, was heavily grazed by livestock or received irrigated agricultural runoff (Hesser and Gangstad 1978). Macrophyte biomass in New Zealand lowland streams is typically highest during the summer and lowest during the winter (e.g., Champion & Tanner 2000, Riis et al. 2003).

3.2 Existing guidelines

There are currently no New Zealand national guidelines for nuisance macrophyte abundance in streams and rivers. Yet, a number of councils have identified nuisance macrophyte growths as an issue of concern in their regions in surveys for the NEMaR project (R. Storey, pers. comm.). Our literature review identified a very limited list of macrophyte guidelines in the international literature (Table 3-1). For lowland streams, some authors have suggested that an “intermediate” level of plant density is beneficial for stream biota (e.g., macroinvertebrates, fish; Sand-Jensen et al. 1989, Collier et al. 1999) but this level has not been not quantitatively defined. In New Zealand, only one Regional Council has designated macrophyte abundance guidelines. Guidelines were designated for Canterbury spring-fed streams as an indicator of nutrient enrichment (ECan 2011); however the rationale for selection of these abundance criteria was not outlined.

Table 3-1: Existing nuisance macrophyte abundance guidelines.

Nuisance threshold	Purpose	Reference
Mountain/hill streams:75% volume	General	Haslam (1978)
Upland floodplain streams:50% volume	General	Haslam (1978)
Lowland streams: 25% volume	General	Haslam (1978)
Abundance achieved by half-shade (about half that of an open channel)	General	Dawson & Kern-Hansen (1979)
<1-50% surface cover	Aesthetics/ recreation	Chambers et al. (1999)
Spring-fed upland streams: 20% emergent, 30% total bottom cover	Nutrient enrichment indicator	ECan (2011)
Spring-fed lower basin streams: 30% emergent, 30% total bottom cover	Nutrient enrichment indicator	
Spring-fed plains streams: 30% emergent, 50% total bottom cover	Nutrient enrichment indicator	
Spring-fed plains streams – urban: 30% emergent,60% total bottom cover	Nutrient enrichment indicator	
100-500 gDW m^{-2}	Recreation in lakes	Chambers et al. (1999)
250 gDW m^{-2}	Ecological condition (O_2 demand)	Jorga and Weise (1977)
400 gDW m^{-2}	Macroinvertebrate biodiversity in lowland streams	Champion and Tanner (2000)

3.3 Guideline types

Guidelines can be based on bottom (stream bed) cover, water surface area cover, biomass, volume or vertical cross-sectional area. We consider that those based on bottom cover are problematic as low-growing plants (e.g., turfs such as *Glossostigma* spp.) can form a high cover across some stream bottoms yet have minimal detrimental impact on aesthetic, recreational, ecological or flow conveyance (i.e., land drainage and flood protection) values. Thresholds based on biomass are also problematic; they have generally been developed for lakes, do not account for differences in water depth (i.e., a larger biomass may be more acceptable in deeper water) and measurements require considerable time and effort to perform.

Thresholds based on volume of watercolumn occupied (usually across transects of pre-defined width, i.e., 1 m), or vertical cross-sectional area (e.g., Riis et al. 2003) are essentially equivalent, and seem most suitable for protecting other stream life from excessive plant abundance and for facilitating flow conveyance. Thresholds based on water surface cover, as opposed to bottom cover, might also be usefully applied to prevent impacts on aesthetics or recreation from floating-leaved species (such as *Mimulus guttatus*, monkey musk) that can form a dense water surface cover but do not necessarily occupy a large volume of the overall water column.

In Appendix B we have provided a fieldsheet template and a worked example to illustrate how macrophyte cross-sectional area or volume (CAV) and water surface area (SA) assessments can be performed. The fieldsheet is a modified version of the Waikato Region macrophyte monitoring protocol (Collier et al. 2007). We have substituted estimates of plant cover as a "percentage of wetted area" (presumably bottom cover) with estimates of plant abundance as a proportion of channel cross-sectional area or volume and water surface area.

3.4 Nuisance species

In New Zealand, both native and introduced macrophyte species can form nuisance growths in streams and rivers, although introduced species are generally most problematic. Native species that can sometimes form nuisance growths (from the perspective of aesthetic, recreational and/or flow conveyance impact) include the charophyte *Nitella hookeri* and the milfoil *Myriophyllum triphyllum* (J. Clayton, pers. comm.). Submerged introduced species commonly forming nuisance growths include *Egeria densa*, *Lagarosiphon major*, *Ceratophyllum demersum* (hornwort), *Ranunculus trichophyllus* (water buttercup), *Potamogeton crispus* (curly pondweed), and less commonly, *Elodea canadensis* (Canadian pondweed). The emergent introduced species *Mimulus guttatus* (monkey musk), *Apium nodiflorum* (water celery) and *Nasturtium officinale* (watercress) can also form nuisance growths in some smaller streams.

3.5 Future work

Information on relationships between instream macrophyte abundance and detrimental impacts on water use activities in the literature remain sparse and although several Regional Councils in New Zealand are now collecting macrophyte abundance data at various sites there is very limited information available to link these data to impairment of specific water use activities. We consider that this should be a priority for future research. Some examples of research that would facilitate the development of robust macrophyte abundance thresholds/guidelines for protection of specific water uses include:

- Examining relationships between instream macrophyte CAV and dissolved oxygen/pH conditions (i.e., diurnal continuous measurement of dissolved oxygen to capture daily minima) to ascertain thresholds above which the health of sensitive fish species may be detrimentally affected (see illustrative example below).
- Examining relationships between macrophyte CAV and macroinvertebrate communities to determine thresholds above which key indices of stream ecological condition (e.g., MCI, %EPT) may be compromised (see example below).
- Compiling existing information from local management authorities, or making measurements of macrophyte abundance, at recreational/water intake/flood risk sites immediately prior to macrophyte control activities (e.g., herbicide spraying, dredging, harvesting) to ascertain levels considered problematic.

Illustrative examples

Some exotic fish species are known to be detrimentally affected by dissolved oxygen concentrations below 5 g m^{-3} (Scott 1982, Wilcock et al. 1998) and recent work on Waikato lowland streams suggests that New Zealand freshwater fish communities should not be exposed to single-day minimum dissolved oxygen concentrations below 3 g m^{-3} and ideally not below 4 g m^{-3} (Franklin 2011). Information from Waikato lowland streams (Wilcock et al. 1998 and Collier et al.1998) on the relationship between stream dissolved oxygen minima and macrophyte abundance (Figure 3-1) suggests that a macrophyte bottom cover in excess of about 38-55% may result in stream dissolved oxygen conditions detrimental to fish. However, this example is for illustrative purposes only. As discussed above, we consider it preferable for stream macrophytes to be quantified as channel cross-sectional area/volume as opposed to a bottom cover, and for relationships with instream values associated with provision of suitable ecological habitat to be established on this basis.

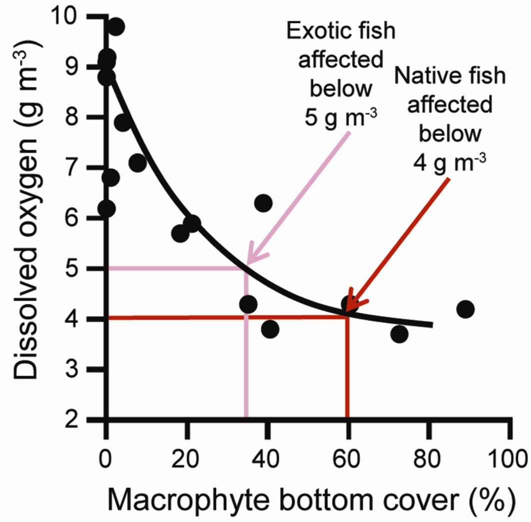

Figure 3-1: Relationship between dissolved oxygen minima and macrophyte bottom cover in 16 Waikato lowland streams during summer. Data from Collier et al. (1998) and Wilcock et al. (1998). Pink and red lines show the dissolved oxygen concentrations below which detrimental effects on sensitive fish species are likely. This corresponds to a macrophyte bottom cover ranging from around ca. 35-60%.

Using Northland Regional Council data we also examined relationships between macrophyte abundance (recorded qualitatively as none, rare, common or abundant) versus macroinvertebrate community indices (MCI, SQMCI, %EPT and taxonomic richness) to determine whether it might be possible to detect a benthic biodiversity threshold relating to macrophyte abundance. We found that MCI (Figure 3-2), SQMCI and taxonomic richness scores tended to decrease in response to greater macrophyte abundance, but the relationships were not significant (ANOVA, p=0.11, 0.18 & 0.48, respectively). No relationship between percent EPT and macrophyte abundance was evident (ANOVA, p=0.62).

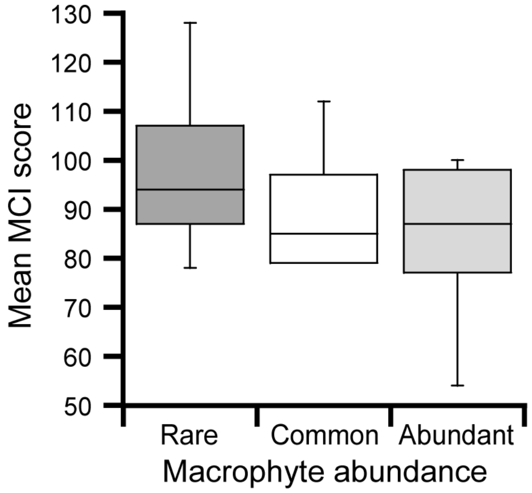

Figure 3-2: Relationship between mean MCI score and maximum macrophyte qualitative abundance in 30 Northland streams during summer. Data from Northland Regional Council. MCI data from 2000-2010 and macrophyte data from 2005-2010. The central line represents the median, the box encloses the interquartile range (25th to 75th percentile) and the bars indicate the data range. Measurements for both parameters were made once in summer each year but at some sites measurements were not made every year.

3.6 Provisional guidelines

As evident from the information presented above, there is still little empirical data that can be used to develop robust nuisance abundance thresholds for instream macrophytes. Nevertheless, Regional Councils urgently require some guidance on this issue so we suggest that a reasonable provisional guideline for protection of instream ecological condition, flow conveyance and recreation would be a channel cross-sectional area/volume (CAV) of ≤50% (Table 3-2). If more than half of a stream channel volume is occupied by macrophyte biomass (native or exotic) we consider that there is *potential* for adverse effects on other stream biota via night-time depletion of dissolved oxygen/alteration of pH, that flow may be impeded with potential for overtopping of banks and flooding to occur, and that recreational use, in particular swimming and angling, could be unsafe and/or impeded. This is consistent with the “half-channel abundance” recommendation of Dawson and Kern-Hanson (1979) and the mid-value suggested by Haslam (1978), while also allowing an “intermediate level of plant density” beneficial to stream invertebrate and fish (Sand-Jensen et al. 1989, Collier et al. 1999). We also consider that a provisional surface area (SA) cover guideline of ≤50% would also be useful for the purposes of protecting aesthetic value, and for recreation in those instances where the dominant plant species have floating leaves but a low below-surface CAV (Table 3-2). However, we suggest that these are general guidelines only and that if more robust site-specific information is available to justify alternative thresholds then that be used in preference to our provisional recommendations.

Table 3-2: Recommended provisional instream macrophyte abundance guidelines.

Nuisance threshold	Purpose
≤50% channel volume/cross-sectional area	Ecological condition, Flow conveyance, Recreation
≤50% surface cover	Aesthetics, Recreation

4 Periphyton abundance guidelines

Section summary:

- A periphyton weighted composite cover (PeriWCC) can be calculated as %filamentous cover + (%mat cover/2) with an aesthetic nuisance guideline of ≥30%.
- Use of upper bound analysis (e.g., quantile regression) is recommended to evaluate periphyton abundance thresholds associated with impacts on benthic biodiversity metrics.
- Based on analysis of the NRWQN matched invertebrate and periphyton cover data, provisional general guidelines of <20%, 20-39%, 40-55% and >55% periphyton weighted aesthetic cover are recommended as indicators of 'excellent', 'good', 'fair' and 'poor' ecological condition, respectively, at sites where other stressors are minimal.
- Further analysis of these periphyton-macroinvertebrate relationships by river type is recommended to refine these provisional guidelines.

4.1 Composite cover guideline

While the *New Zealand Periphyton Guideline* provides separate aesthetic impact guidelines for identifying nuisance periphyton filamentous (≥30%) and mat (≥60%) cover, a composite cover guideline is also useful for instances where both filamentous growths and mats occur. The threshold for aesthetic nuisance mat cover is twice that for filamentous cover, so the composite weighted composite cover (PeriWCC) can be defined as filamentous + mat/2 with a nuisance guideline of ≥30%. Examples of PeriWCC calculations and compliance with the aesthetic guideline are shown in Table 4-1.

Table 4-1: Worked examples of Periphyton Weighted Composite Cover (periWCC) and compliance with proposed combined guideline. Proposed nuisance guideline is ≥30%.

Filamentous Cover (%)	Mat Cover (%)	periWCC	Compliance
20	40	40	No
25	8	29	Yes
10	50	35	No
5	58	34	No
18	26	31	No
15	40	35	No
32	0	32	No
0	64	32	No

4.2 Further evaluation of benthic biodiversity guideline

We have performed some further evaluation of the benthic biodiversity guideline using paired periphyton-macroinvertebrate data from Environment Southland and the NRWQN database. The Environment Southland dataset consisted of periphyton abundance as chlorophyll *a* and MCI scores. The NRWQN database has periphyton abundance as visually assessed cover classes and various macroinvertebrate indices.

Inferring periphyton/invertebrate metric relationships from field data is complicated by the other stressors that also affect invertebrate communities (e.g., temperature, sediment, toxicants, habitat constraints). Consequently, traditional central tendency (regression) analysis is not appropriate for the identification of thresholds. Examination of the upper bounds of the data relationships using upper percentiles and/or by drawing upper bound lines by eye is a more robust approach.

4.2.1 Chlorophyll *a* versus MCI

Paired periphyton chl *a* and MCI data from 70 sites in Southland were plotted (Figure 4-1). The plot shows that where chl *a* is ≥200 mg m^{-2} the MCI is usually <100 indicating less than ‘good’ condition and where chl *a* is ≥100 mg m^{-2} the MCI is usually <120 indicating less than ‘excellent’ condition. These “upper bound” thresholds suggest that, if other stressors are minimal, then chl *a* values of <100 mg m^{-2} should result in MCI ≥120, reflecting “clean water” conditions (Stark and Maxted 2007) and that chl *a* values of <200 mg m^{-2} should result in MCI >100, reflecting “possible mild pollution”.

Overall, these data suggest that the *New Zealand Periphyton Guideline* of 50 mg chl *a* m^{-2} is appropriate for protecting “excellent” ecological condition (MCI>120) in typical Southland streams, but a higher threshold of 100 mg chl *a* m^{-2} may be warranted in some cases where other stressors on macroinvertebrates are minimal. We suggest that other councils might follow the simple approach demonstrated here (i.e., correlating MCI scores with chl a) to evaluate the broad applicability of the 50 mg m^{-2} benthic biodiversity threshold in their region. If sufficient representation of different river types (e.g., REC classes) is available, then this approach could also be applied separately by river type. It would also be useful to attempt a further national scale analysis in the next phase of this project if sufficient paired periphyton chl*a* and macroinvertebrate data are available from Regional Councils.

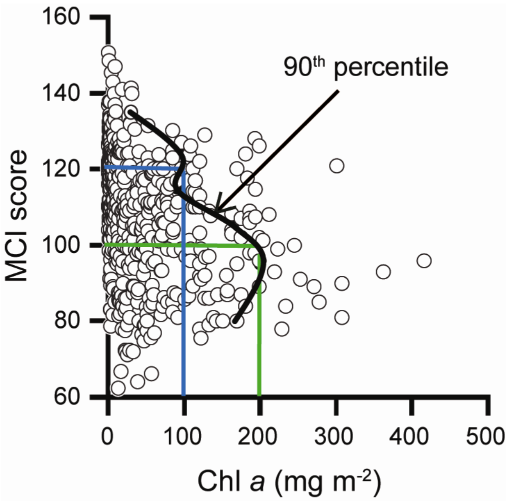

Figure 4-1: Paired periphyton chlorophyll *a* values versus macroinvertebrate community index scores for 70 sites in Southland from 2001 to 2008. The green lines show that above a chl *a* value of 200, MCI scores are usually less than 100. The blue lines show that above a chl *a* value of 100, MCI scores are usually less than 120. The black line is the 90th percentile line which is broadly consistent with the thresholds noted above.

4.2.2 Periphyton cover versus macroinvertebrate indices

Many councils assess periphyton cover visually as percent of different cover classes, but there are no existing guidelines relating these classes to invertebrate community metrics. To fill this information gap for the two main cover classes (i.e., filamentous algae and mats), the NRWQN data were analysed to investigate relationships between periphyton cover and macroinvertebrate metrics in paired samples collected under summer low flow conditions. We used the weighted composite nuisance cover metric of percent filamentous algal + percent mat/2 (periWCC) as the invertebrate metric stressor because this had slightly stronger correlations with the various invertebrate metrics than percent filamentous algae + mats (see Appendix C).

The relationships between composite nuisance cover and four key invertebrate metrics show negative relationships between cover and metric scores (Figure 4-2, Figure 4-3). We suggest that the upper percentile curves are useful for identifying the upper periphyton composite cover level that could maintain various invertebrate metric values, *if other stressors are minimal*. For example, the 90th percentile line in Figure 4-2 could be used to define the composite nuisance periphyton target for a general QMCI target of >5. This indicates that, in the absence of significant other stressors, a composite nuisance periphyton cover of <40% should sustain QMCI >5. Lower percentile curves (e.g., 80th percentile) could be used where other stressors are expected to be influencing the invertebrate communities, whereas higher percentiles (e.g., 95th) could be used if it is considered that all other conditions are highly suitable for sensitive invertebrates.

The 90th percentile composite nuisance periphyton cover levels associated with ‘excellent’ condition (QMCI >5.99 and MCI >119), ‘good’ condition (QMCI >5.00-5.99 and MCI 100-119), ‘fair’ condition (QMCI 4.00-4.99 and MCI 80-99) and ‘poor’ condition (QMCI <4.00 and MCI <80) were ca. <20%, 20-39%, 40-55% and >55% respectively (Figure 4-2). For percent EPT if we use the USEPA’s Biological Condition Scoring Criteria (Plafkin et al. 1989) and nominally assign condition classes to these criteria (i.e., %EPT >75% excellent, 50-75%

good, 25-50% fair, <25% poor) then corresponding nuisance periphyton cover levels are very similar to those for QMCI/MCI (Figure 4-3). For EPT richness there are no recommended thresholds to indicate macroinvertebrate community condition classes. However, the similarity of thresholds identified for periphyton cover on the basis of QMCI, MCI and percent EPT scores, suggests that these values could form the basis of provisional general periphyton cover thresholds to protect benthic biodiversity. It is probably worthwhile to explore how/whether these relationships between periphyton composite cover and macroinvertebrate metrics vary significantly between river type (e.g., upland and lowland rivers, by REC class) and this is suggested as a task for the next phase of this project.

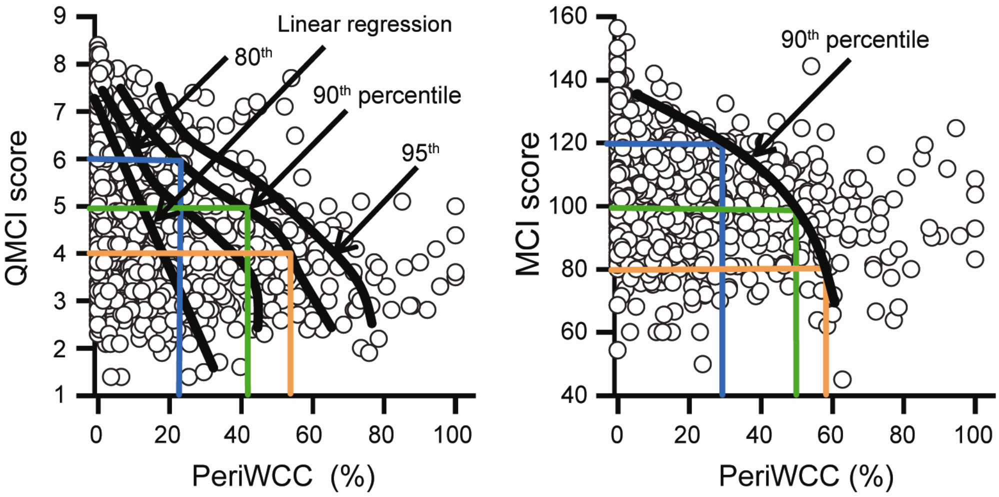

Figure 4-2: Relationships between weighted composite percent nuisance periphyton cover (PeriWCC) and macroinvertebrate community index scores based on NRWQN data 1990-2007 under summer lowflow conditions. The central tendency regression line (for QMCI only) and the upper percentile lines are shown. The blue, green and orange lines indicate apparent thresholds representing excellent, good and fair condition, respectively based on QMCI and MCI scores.

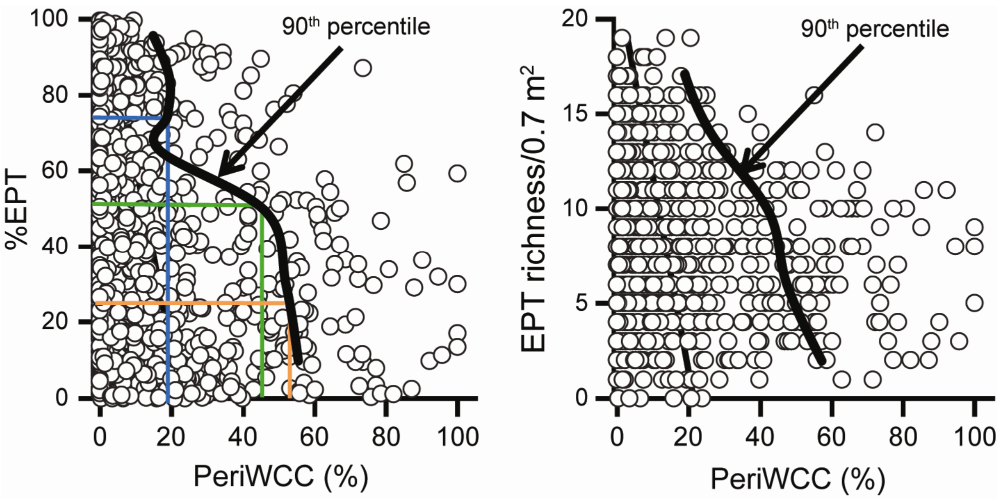

Figure 4-3: Relationships between weighted composite percent nuisance periphyton cover (PeriWCC) and macroinvertebrate community EPT values based on NRWQN data 1990-2007 under summer lowflow conditions. The 90th percentile lines are shown. The blue, green and orange lines indicate apparent thresholds representing excellent, good and fair condition, respectively, based on %EPT values.

5 Clarification of aspects of the New Zealand Periphyton Guideline

Section summary:

- Data used to derive the *New Zealand Periphyton Guideline* calculated accrual period using whole-year (not summer) mean daily flow data, a flow record that corresponded to matched periphyton and nutrient measurements, a flood defined as three times the median flow and no flood interval filter period.
- An analysis using the River Environment Classification database has confirmed that sites used to derive the *New Zealand Periphyton Guideline* were a good representation of hill-fed, cobble bed New Zealand rivers. Other river types were not well represented and these are considered to comprise ca. 30% of all New Zealand river segments.

5.1 Accrual period

5.1.1 Introduction

Periphyton growth rate and the period of suitable flow conditions for accrual are key determinants of the biomass present at a point in time. Determining accrual period is not trivial. In the majority of streams, high flows periodically ‘‘reset’’ algal biomass through the loss processes of shear, abrasion, and bed disturbance. An algal biofilm’s resilience will be affected by the species composition and age of the attached biofilms, together with site-specific river sediment and turbulence characteristics. The sensitivity of algal growths to being sheared from the riverbed is dependent on instantaneous flow (i.e., strong peak flow dependence). However, the daily mean flow has frequently been used as a more pragmatic measure for ease of calculation of hydraulic stress from flow statistics.

The frequency of flow events that exceed 3x the median flow per year (FRE3, expressed as number per year, or number per season for a seasonal analysis) is used as an index of the amount of disturbance experienced by instream organisms. The FRE3 statistic, introduced in Clausen and Biggs (1997), provides an index of flow variability that has proved useful for periphyton prediction. The annual FRE3 is sometimes used to calculate the typical accrual period (days) as 365/Annual FRE3.

5.1.2 Calculation of accrual period

Use of the *New Zealand Periphyton Guideline* requires an understanding of the ‘mean days of accrual’ which is related to flood frequency calculation. However, the document does not define a method to calculate this parameter. Users need to know (1) whether annual or summer flow data should be used, (2) whether instantaneous or daily flow data should be used, (3) the length of flow record to use, (4) which flood frequency parameter to use, and (5) whether a time interval or ‘filter period’ between flood peaks should be used.

1. *Annual versus summer flow data*: The publications deriving the nutrient guidelines (including Clausen & Biggs 1997, Biggs 2000) used annual data (median flow and daily means) for flood frequency calculation. For consistency, this is the approach that should be taken when using the *New Zealand Periphyton Guideline*. However, site-specific derivation could be based on considering the summer period, as the nutrient

guidelines note that this is usually the period of interest for effects on recreation and aesthetics and is often the period when maximum light and water temperature produce maximum plant biomass. For example, Hickey et al. (2004) found that the FRE3 for the Manawatu and Ruamahanga Rivers varied considerably using annual data (13.7 & 19, respectively) versus summer data (7 & 10.6, respectively) (see Appendix D), indicating marked differences between annual and seasonally based derivations.

2. *Instantaneous versus daily flow data*: Daily mean flow data were used to derive flood frequencies in the publications used to derive the *New Zealand Periphyton Guideline*. However, since instantaneous flow data is more directly relevant to periphyton scour than daily means, site specific applications could use daily maximum flows rather than daily mean flows as the former measures the peak flow that is expected to drive bed movement and velocity-induced periphyton sloughing.

3. *Length of flow record*: Flood frequencies used in the derivation of the *New Zealand Periphyton Guideline* were calculated for the 12-15 month period that corresponded directly to measurements of periphyton biomass and nutrient concentrations. When applying the *Guideline* users should carefully consider the length of flow record to use. A longer record is not necessarily better if there have been significant changes to the river system/catchment over this period. The length of flow record to use should, as far as possible, be consistent with available nutrient and periphyton data and climate conditions (e.g., El Nino vs. La Nina) over the period of interest.

4. *Flood frequency parameter*: FRE3 was used to calculate flood frequency and accrual period for data used in the *New Zealand Periphyton Guideline*. However, a flood of greater (e.g., FRE4) or lesser magnitude (e.g., FRE1 or 2) may be a more appropriate threshold for periphyton scour in some river systems. Local knowledge should be used to select the appropriate flood frequency parameter wherever possible.

5. *Flood interval filter period* – For calculation of flood frequency this parameter is the period that must elapse following a flood before a new flood event is recognised. This period is required to allow the algae to begin significant growth following a flood event and has a marked effect on the calculated accrual period. It is understood that the relationships that formed the basis of the *New Zealand Periphyton Guideline* used no filter period (M. Duncan, pers. comm.). The filter period has been variously applied elsewhere as a 5 d interval (Snelder et al. 2004, Henderson and Diettrich 2007) and a 10 d interval (Snelder et al. 2005). If using the *New Zealand Periphyton Guideline*, for consistency with the original research from which those guidelines were derived, no filter period should be used. However, some form of filter period might be justified in site specific applications. For example, Hickey (2003) found that a 1-day period was most appropriate for the Ruamahanga River.

5.2 River types where the existing nutrient guidelines apply

The nutrient guidelines presented in *The New Zealand Periphyton Guideline* were based upon data from 30 river sites around New Zealand, predominantly in hill-fed, cobble-bed rivers. Recently, an analysis was undertaken under NIWA's core-funded *Sustainable Water Allocation Programme* to ascertain the 'representativeness' of the dataset in the context of the wider New Zealand rivers network using the River Environment Classification (REC) database. The full analysis is provided in Appendix E. The main findings of the analysis were:

- The 30 river sites used for derivation of the nutrient guidelines were a good representation of hill-fed, cobble-bed rivers in New Zealand.
- However, other river types, notably low-order lowland streams in warm areas, were not represented. Specifically, river network segments that were poorly or not represented were those with fine substrate, those with medium-sized substrate and high nutrient levels and those with coarse substrate, low-medium nutrients and high FRE3.
- Unrepresented river types are likely to account for about 30% of all river segments.
- The dataset did not account for likely regional differences in periphyton-environment relationships due to its relatively small size.
- The limitations of the nutrient-flow-periphyton relationships developed were clearly stated.

The results of the above analysis provide clarification of those river types where application of the *New Zealand Periphyton Guideline* nutrient thresholds is appropriate. For other river types we suggest that the BBN models presented later in this report are a useful starting point.

6 National scale analysis of factors regulating periphyton abundance

Section summary:

- Bivariate correlation analysis identified nutrient concentrations and temperature as the environmental variables most strongly related to periphyton filamentous and composite cover in large rivers.
- Inspection of bivariate plots identified the following thresholds associated with low risk of periphyton filamentous cover exceeding the 30% aesthetic nuisance threshold:

  95th percentile temperature <16°C, average total nitrogen <300 mg m^{-3}, average DIN <250 mg m^{-3}, average DRP <6 mg m^{-3}, average substrate index <4 (average small gravel), average annual $FRE3_{inst}$ >25 and average streambed light <300 µmol m^2 s^{-1}.
- Stepwise linear regression analysis identified temperature, nutrients and streambed lighting as the most important variables controlling annual maximum and average filamentous periphyton cover in large rivers. However, flood frequency, substrate size and macrograzer density also featured in the models.

6.1 Introduction

The National Rivers Water Quality Network (NRWQN) database was used to perform a national scale analysis of factors regulating periphyton abundance. In the NRWQN periphyton abundance is quantified as percentage covers of filamentous algae and mats. The NRWQN database also contains information on the predominant physico-chemical and biological factors considered to regulate instream periphyton abundance (i.e., streambed lighting, flood frequency, nutrients, temperature, substrate and invertebrate macrograzer density (see Appendix C for a list of invertebrate macrograzers). We used bivariate correlation and inspection of bivariate plots to evaluate potential linear and non-linear relationships and thresholds, and stepwise multiple regression to model these relationships. Note: all parameters used in these analyses are expressed as average values for the 17 year dataset unless otherwise stated. Note also that twelve NRWQN sites were excluded from the analysis for various reasons, leaving a dataset of 65 sites (see Appendix C for further explanation).

6.2 Bivariate correlation

Bivariate correlation analysis showed that annual filamentous maximum (AFM) periphyton cover was correlated with both corresponding site averages of annual mat maximum (AMM) cover and annual composite maximum cover (ACM) (Table 6-1). There were also very strong correlations between the annual maximum and annual average filamentous, mat and composite covers (AFA, AMA, ACA) (Table 6-1).

Annual filamentous maximum (AFM) was most strongly correlated with nutrient concentrations (particularly nitrogen) and temperature. Relationships with streambed lighting, flood frequency and macrograzer density were not statistically significant. ACM showed a generally similar order of environmental correlations to AFM. Average annual maximum mat (AMM) cover had weaker correlations with environmental variables than AFM and ACM and none were statistically significant.

Using nutrient data obtained at lower than median flows and using site medians, rather than means, did not generally result in stronger correlations with annual maximum periphyton covers, except for TP which is strongly influenced by high flows (Table 6-1).

$FRE3_{inst}$, (calculated on hourly average flows with no filter period) had similar correlations with AFM, AMM and ACM as FRE1 (5-day filter period) and stronger correlations than FRE3 calculated from daily mean flows, with or without a 5-day filter period (Table 6-1).

The various forms of N and P were strongly inter-correlated and mean temperature was also strongly correlated with the 95th percentile temperature ($r = 0.93$) (Table 6-2).

Table 6-1: Pearson correlations between normalised average maximum periphyton cover (as Annual Filamentous Maximum (AFM), Annual Mat Maximum (AMM), Annual Composite Maximum (ACM), Annual Mat Average (AMA), Annual Filamentous Average (AFA), Annual Composite Average (ACA)) and environmental variables. Data for 65 NRWQN sites. Values in bold are statistically significant (r≥0.24, p<0.05). Log = log 10 transformed and √ = square root transformed.

√ AFM	√ AMM	√ ACM
√ AFA **0.97**	√ AMA **0.96**	√ ACA **0.95**
√ ACM **0.95**	√ ACM **0.72**	√ AFM **0.95**
√ ACA **0.92**	√ ACA **0.69**	√ AFA **0.90**
√ AMA **0.53**	√ AFM **0.51**	√ AMM **0.72**
√ AMM **0.51**	√ AFA **0.49**	√ AMA **0.71**
Log NH_4 **0.45**	Log TN< median flow 0.22	Log TN **0.43**
Log TN **0.44**	Log TN10%tile 0.20	Log TN10%tile **0.43**
Log TN10%tile **0.44**	Streambed light 0.19	Log NH_4**0.39**
Temperature 95% **0.43**	Log NO_3< median flow 0.19	Log TN< median flow **0.38**
Log NH_4< median flow **0.41**	Log DIN< median flow 0.19	Temperature 95%**0.38**
Temperature average **0.41**	Log TN 0.18	Log NH4< median flow **0.36**
Log TN< median flow **0.38**	Log NO_3 0.17	Temperature average **0.36**
Log DRP **0.36**	Log DIN 0.17	Log NO_3 **0.36**
Log TP10%tile **0.36**	Log DIN/DRP 0.14	Log DIN **0.36**
Log NO_3 **0.36**	Substrate index -0.13	Log TP10%tile **0.34**
Log DIN **0.36**	Log NH_4< median flow 0.12	Log DRP **0.33**
Log TP<median flow **0.33**	Log NH_4 0.11	Log TP<median flow **0.31**
Log DRP< median flow **0.31**	$FRE3_{Inst\ no\ filter}$ -0.11	Log NO_3< median flow **0.29**
Log TP **0.31**	Log TP<median flow 0.10	Log DIN< median flow **0.29**
Log DRP10%tile **0.30**	Log DRP< median flow 0.10	Log TP **0.28**
Log DIN< median flow **0.27**	Log TP10%tile 0.09	Log DRP< median flow **0.28**
Log NO_3< median flow **0.26**	Log DRP 0.09	Log DRP10%tile **0.27**
Streambed light 0.13	√ macrograzers -0.09	Streambed light 0.15
$FRE3_{Inst\ no\ filter}$ -0.13	$FRE1_{mean\ daily,\ 5\ d\ filter}$ -0.09	Log DIN/DRP 0.14
√ macrograzers 0.12	$FRE3_{mean\ daily,\ 5\ d\ filter}$ -0.08	$FRE3_{Inst\ no\ filter}$ -0.14
$FRE1_{mean\ daily,\ 5\ d\ filter}$ -0.12	DRP10%tile 0.07	$FRE1_{mean\ daily,\ 5\ d\ filter}$ -0.13
Log DIN/DRP 0.11	Temperature 95%0.07	Substrate index -0.12
$FRE2_{mean\ daily,\ 5\ d\ filter}$ -0.11	Temperature average 0.06	√ macrograzers 0.11
$FRE3_{mean\ daily,\ 5\ d\ filter}$ -0.08	$FRE2_{mean\ daily,\ 5\ d\ filter}$ -0.05	$FRE2_{mean\ daily,\ 5\ d\ filter}$ -0.09
Substrate index -0.08	TP -0.01	$FRE3_{mean\ daily,\ 5\ d\ filter}$ -0.08

Table 6-2: Intercorrelations amongst site mean and 10th percentile (low flow) concentrations of N and P. Data for 65 NRWQN sites included in the periphyton analysis. Values in bold are statistically significant (r≥0.24, p<0.05). Log = log 10 transformed.

	Log DRP	Log DIN	Log DRP10%ile	Log DIN10%ile	Log TP	Log TN	Log TP10%ile
Log DIN	**0.67**						
Log DRP10%tile	**0.96**	**0.54**					
Log DIN10%tile	**0.63**	**0.98**	**0.54**				
Log TP	**0.47**	**0.45**	**0.45**	**0.43**			
Log TN	**0.73**	**0.95**	**0.60**	**0.90**	**0.50**		
Log TP10%tile	**0.74**	**0.56**	**0.75**	**0.54**	**0.85**	**0.65**	
Log TN10%tile	**0.75**	**0.93**	**0.65**	**0.90**	**0.48**	**0.99**	**0.67**

6.3 Bivariate plots to evaluate linear and non-linear relationships and thresholds

Relationships between annual filamentous maximum (AFM) cover and individual environmental variables were also examined using bivariate plots (Figure 6-1). Note that the AFM data used in these plots has been square root (sqrt) transformed and that a sqrt AFM value of 5.6 corresponds to AFM cover of 30% (the existing aesthetic nuisance guideline). We used this guideline to identify potential thresholds for most of the environmental parameters above which these variables were considered to contribute to nuisance periphyton growth. Where sqrt AFM values exceeded 5.6 we identified the corresponding value for the environmental variable above (or below in the case of FRE3) which the majority of datapoints were placed. In some cases several outliers (above or below the threshold) were identified. These cases are shown in Figure 6-1 and discussed below.

Site TU2 (Tongariro at Turangi) was a high outlier in relation to temperature, TN and DIN. This site has relatively high DRP (12.9 g m^{-3}) and flow regimes managed for hydropower generation that result in truncated flow recessions. A longitudinal study of periphyton biomass along the regulated and unregulated areas of the Tongariro, including site TU2 (Quinn and Vickers 1992), found marked increases in periphyton at the managed flow sites (c.f. natural flows). Sites TK5 (Hakataramea) and DN4 (Lower Clutha) were high outliers in relation to DRP, TN and DIN – unusual hydrology below the Roxburgh Dam on the Clutha (low FRE3 but daily water level fluctuations) may contribute to the unusually high periphyton cover at AX4, but there were no obvious reasons for the TK5 outlier. DN3 (Lower Taieri) was a high outlier on the DIN plot (AFM = 50% at DIN of 54 mg m^{-3}), but had a moderate TN of 327 mg m^{-3}, suggesting that perhaps organic N was contributing to periphyton biomass at this site. The outlying low temperature response of periphyton cover at GS1, was likely due to its sandy bed (SI = 2.6).

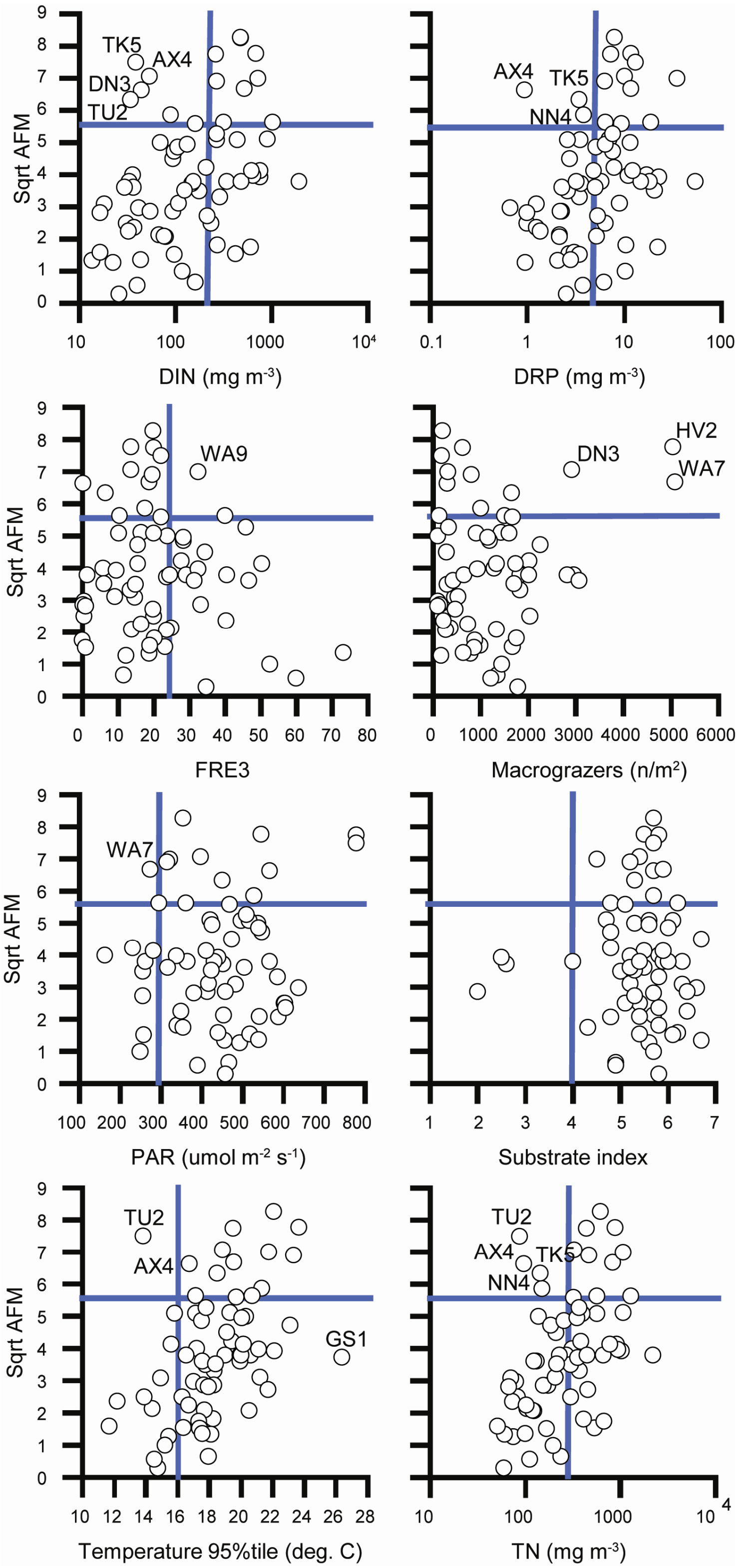

Figure 6-1: Environmental variables versus percentage filamentous algal cover (square root of annual maximum) at 65 NRWQN sites (1990-2006). Horizontal blue lines indicate 30% cover (Sqrt 30 = 5.6) and vertical blue lines represent apparent thresholds for nuisance cover. PAR is average streambed irradiance.

There was no strong evidence of macrograzer influence on AFM (Figure 6-1) as 3 sites with high AFM had amongst the highest macrograzer densities. This indicates that relationships between periphyton and grazers are more complex than can be captured by the comparison of an average summer grazing invertebrate density and annual maximum cover. All other relationships were used to derive generally applicable thresholds for key individual factors to achieve AFM compliance with the *New Zealand Periphyton Guideline* aesthetic guideline of 30% (Table 6-3).

Table 6-3: Generally applicable thresholds for limiting Average Annual Filamentous Maximum (AFM) cover to below the 30% cover nuisance threshold as indicated by the NRWQN (1990-2006).

Environmental variable/predictor	Threshold
95th percentile temperature (°C)	16
TN (mg m^{-3})	300
DIN (mg m^{-3})	250
DRP (mg m^{-3})	6
Substrate index	4 (average small gravel)
$FRE3_{inst}$ (n y^{-1})	25
Streambed lighting (PAR, µmol m^{-2} s^{-1})	300

6.4 Multiple regression

The best model ($F_{7,57}$ = 7.1) identified to predict annual filamentous maximum (AFM) cover included 7 significant environmental variables and explained 46% of the variance (Table 6-4). TN was the strongest influence in this model and carried information on other strongly correlated nutrient variables, especially nitrate (r = 0.94), ammonium (r = 0.84) and DRP (r = 0.72) (all correlations based on log transformed data), that therefore dropped out of the stepwise model. However the DIN:DRP ratio was a significant factor, with a negative co-efficient, indicating that low levels of P in relation to N constrain AFM amongst these sites. This intercorrelation between nutrient variables in the data set constrains the use of the model to investigate the *independent* effects of N and P on the risk of filamentous algae blooms.

The next strongest influences in the AFM model were average light at the streambed and summer temperature (represented by the 95%ile temperature). Low substrate index (SI) values (i.e., small substrate size) and FRE3 (no filter period, based on daily mean flow) also had weak negative influences on AFM in the model whereas ammonium at flows below the median had a positive influence (Table 6-4).

Table 6-4: Summary of stepwise multiple regression model of environmental variables regulating Annual Filamentous Maximum cover (AFM, square root transformed) at 65 NRWQN sites.

Variable	Coefficient	s.e. of Coeff	t-ratio	prob	Cumulative r^2
Constant	-5.98463	1.924	-3.11	0.0029	
95%ile Temperature (°C)	0.249642	0.08516	2.93	0.0048	18.3
Log TN (mg m^{-3})	1.7648	0.9148	1.93	0.0587	25.1
Streambed light (MJ m^{-2} d^{-1}) [1]	0.333255	0.09105	3.66	0.0006	35
1/Substrate Index	-7.63231	3.652	-2.09	0.0411	38
Log (DIN/DRP)	-0.94884	0.5696	-1.67	0.1012	41.3
FRE3 (Daily mean no filter)	-0.04037	0.02749	-1.47	0.1475	43.5
Log NH_4 at < median flows (mg m^{-3})	1.84719	1.093	1.69	0.0966	46.2

[1] Note that streambed light as MJ m^{-2} d^{-1} can be converted to µmol m^{-2} s^{-1} by multiplying by 53.2.

Comparison of model predictions and measurements indicates that it is unlikely that AFM will exceed the *New Zealand Periphyton Guideline* 30% cover threshold for aesthetic nuisance effects if the regression model prediction is for <15% cover (only 1 outlier site AX4 Clutha below Roxburgh Dam) (Figure 6-2). This suggests the model could be used to identify conditions where the risk of nuisance filamentous cover is low. However, there is a large amount of variation in predicted and observed AFM at higher levels of predicted AFM, at which that the model can only be considered to be broadly indicative. Including more sites with high AFM in the future would likely improve the reliability of such models in this range.

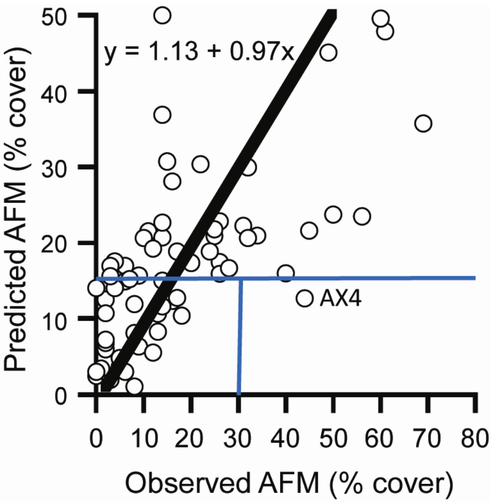

Figure 6-2: Comparison measured Annual Filamentous Maximum (AFM) percentage cover and predictions of the stepwise multiple regression model in Table 6-4.

The stepwise multiple regression model for annual filamentous average (AFA) (cover ($F_{9,52}$ = 7.92) included 9 significant environmental variables and explained 58% of the variance (Table 6-5, Figure 6-3). The top three variables in the AFA regression equation were the same as in the model for AFM, again indicating that temperature, light and nutrients are the most important factors. FRE2 was the most significant hydraulic variable for AFA (c.f. FRE3 for AFM). Ammonium concentration at flows below the median was again a significant influence but was weaker than macrograzer density and conductivity. The influence of conductivity probably reflects the minor roles of other minerals in supporting periphyton growth.

Table 6-5: Summary of stepwise multiple regression model of factors influencing Annual Filamentous Average (AFA) cover (square root transformed) at 65 NRWQN sites.

Variable	Coefficient	s.e. of Coeff	t-ratio	prob	Cumulative r^2
Constant	-4.23351	1.595	-2.65	0.0105	
95%ile temperature (°C)	0.105932	0.05623	1.88	0.0652	18.5
Streambed light (MJ $m^{-2}d^{-1}$) [1]	0.236974	0.05101	4.65	<0.0001	24.8
Log TN (mg m^{-3})	1.58534	0.6214	2.55	0.0137	35.1
Log (DIN:DRP)	-0.86047	0.3434	-2.51	0.0154	38.8
FRE2 (daily means, 5 day filter)	-0.07102	0.03228	-2.2	0.0323	41.0
1/Substrate Index	-18.6646	6.077	-3.07	0.0034	43.7
Sqrt macrograzers m^{-2}	-0.01886	0.009002	-2.09	0.0411	51.7
Log Conductivity	1.7128	0.8459	2.02	0.0480	55.0
Log NH_4-N<median flows (mg m^{-3})	1.17595	0.6299	1.87	0.0676	57.9

[1] Note that streambed light as MJ m^{-2} d^{-1} can be converted to µmol m^{-2} s^{-1} by multiplying by 53.2.

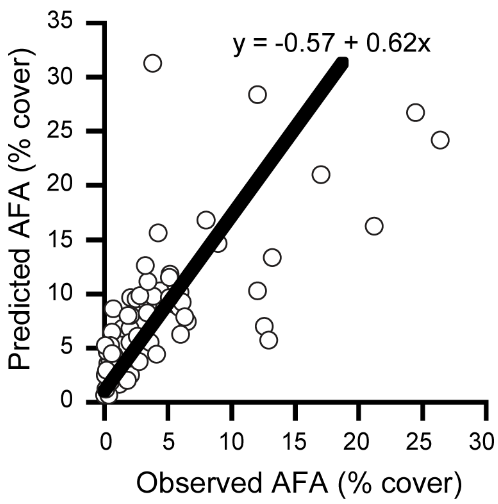

Figure 6-3: Comparison measured annual filamentous average (AFA) cover and predictions of the stepwise multiple regression model in Table 6-5.

Stepwise regression models were also developed that excluded consideration of TN and TP because some users only sample dissolved nutrients. These models explained slightly less variance than those including total nutrients but are still useful for evaluating the risk of periphyton occurring (Table 6-6,Table 6-7).

Table 6-6: Summary of stepwise multiple regression model of factors (excluding total nutrients) influencing Annual Filamentous Maximum cover (AFM, square root transformed) at 65 NRWQN sites.

Variable	Coefficient	s.e. of Coeff	t-ratio	prob	Cumulative r^2
Constant	-4.35632	1.771	-2.46	0.0169	
95%ile temperature (°C)	0.283104	0.08317	3.4	0.0012	18.3
Streambed light (MJ $m^{-2}d^{-1}$) [1]	0.300701	0.09057	3.32	0.0016	23.2
Log DRP (mg m^{-3})	0.675664	0.6036	1.12	0.2676	30.3
Log NH_4-N<median flows (mg m^{-3})	2.53583	0.9098	2.79	0.0072	37.7
1/Substrate Index	-7.97501	3.713	-2.15	0.0359	41.1
FRE3 daily means no filter	-0.04137	0.02805	-1.47	0.1457	43.2

[1] Note that streambed light as MJ m^{-2} d^{-1} can be converted to µmol m^{-2} s^{-1} by multiplying by 53.2.

Table 6-7: Summary of stepwise multiple regression model of factors (excluding total nutrients) influencing Annual Filamentous Average cover (AFA, square root transformed) at 65 NRWQN sites.

Variable	Coefficient	s.e. of Coeff	t-ratio	prob	Cumulative r^2
Constant	-3.10757	1.855	-1.68	0.0998	
95%ile temperature (°C)	0.134438	0.0575	2.34	0.0232	18.5
Streambed light (MJ m^{-2} d^{-1}) [1]	0.208089	0.05247	3.97	0.0002	24.8
Log DRP (mg m^{-3})	0.645696	0.4222	1.53	0.1321	30.9
FRE3 daily means no filter	-0.03334	0.01639	-2.03	0.0469	33.1
Log NH_4-N<median flows (mg m^{-3})	1.71823	0.522	3.29	0.0018	41.6
1/Substrate Index	-19.0166	6.672	-2.85	0.0062	44.7
Log Conductivity	1.65552	0.8961	1.85	0.0703	47.3
Sqrt macrograzers m^{-2}	-0.01177	0.00884	-1.33	0.1887	53.1

[1] Note that streambed light as MJ m^{-2} d^{-1} can be converted to µmol m^{-2} s^{-1} by multiplying by 53.2.

This analysis shows that multiple regression models have some potential for assessing the risk of nuisance periphyton occurring. However, they also have limitations, in particular that that (i) intercorrelation between some variables (notably nitrogen and phosphorus) in the NRWQN dataset reduce their use to investigate single limiting nutrient effects (e.g., constraint of periphyton biomass development when nitrogen levels are high but phosphorus is low and potentially limiting, and vice versa); and (ii) the models assume linear relationships between variables that we know to involve threshold (e.g., particle size) and saturation effects (e.g., light and nutrients). The BBN modelling approach is considered to be better suited to dealing with these constraints.

7 Development and use of general macrophyte and periphyton BBN models

Section summary:

- Two general Bayesian Belief Network models have been developed to predict the risk of nuisance periphyton (>30% filamentous algal cover) and macrophyte (>50% channel cross-sectional area/volume) growths.
- These models include variables related to stream bed lighting, flow velocity and/or flood frequency, substrate size, water temperature, nutrients and grazer density.
- National and regional scale testing of the models indicates that they correctly predict the risk of nuisance plant abundance at most sites.
- The BBNs are intended for use as a risk assessment tool that takes into account all the influences on instream periphyton or macrophyte growth, not just nutrients. Scenarios to which the BBN could be applied to scope effects on the risk on instream nuisance plant growth include hydro dam evaluation, water storage for irrigation of agricultural land, sewage treatment upgrade and riparian shade management.
- The BBNs may also be used to identify those situations where setting of river nutrient limits is inappropriate or of low priority and can be used to scope the range of likely nutrient limits in sensitive rivers.

7.1 Overview of model development and use

Our first step in BBN model development was to use the literature review to draw conceptual linkage models of proximate variables influencing development of instream periphyton and macrophytes (Figure 7-1). Next, two to four states were defined for each variable that reflect effect thresholds (e.g., substrate states were defined as sandy/silt vs. gravel vs. cobble/boulder/bedrock. Nuisance plant thresholds were defined filamentous periphyton cover >30% (reflecting the *New Zealand Periphyton Guideline* aesthetic guideline) and macrophyte cross-sectional area/volume >50% reflecting our provisional recreational, flow conveyance ad ecological habitat guidelines. Each state was then assigned a weighting between 0 and 1 reflecting its influence on the likelihood of the nuisance plant threshold being exceeded if the states of all other factors were optimal (based on expert opinion). For periphyton we also used the NRWQN analysis to inform the assigning of states and weightings for each parameter. We then constructed a matrix of all 2952 possible combinations of the factor states (in Excel), multiplied each combination of weightings together, and scaled their products by the maximum product, to generate an overall rating of nuisance plant growth risk for each combination of variable states. This matrix and associated ratings were copied into a conditional probability table in the BBN software (Netica 4.02, Norsys Software Corporation, Vancouver, Canada) so that combined influences on the risk of nuisance plant occurrence could be calculated and visualised rapidly.

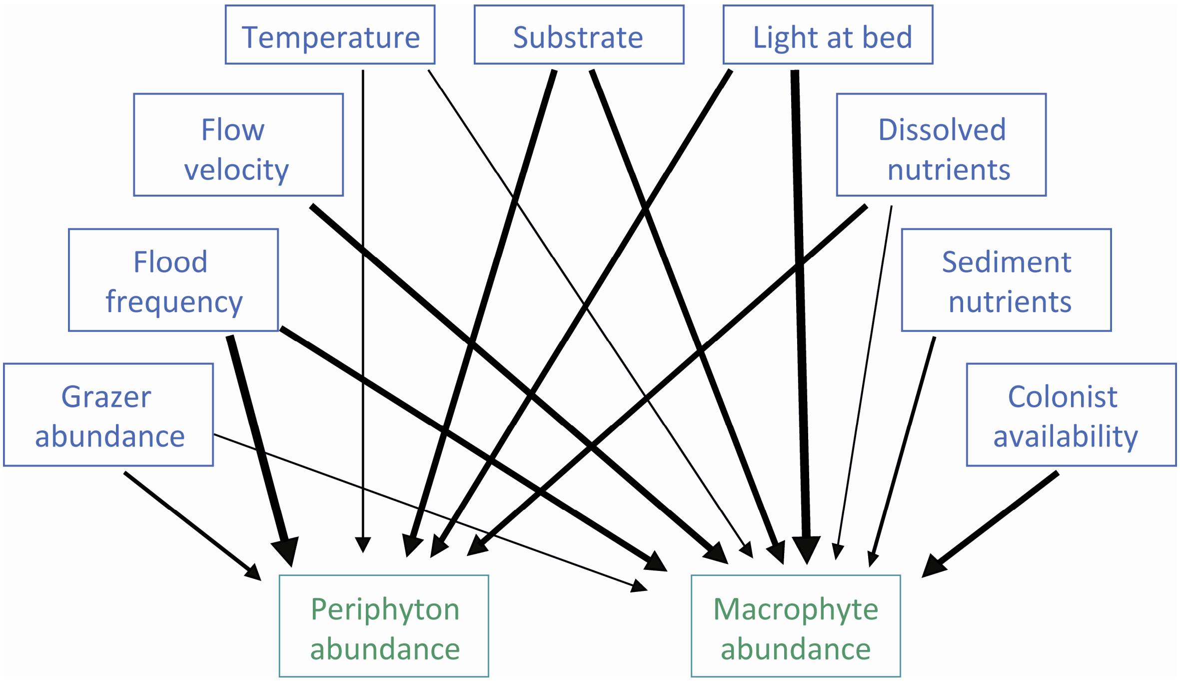

Figure 7-1: Key variables regulating instream nuisance plant abundance. Width of arrows indicates relative degree of influence. Note that flow velocity and colonist availability can effect both macrophyte and periphyton abundance. However, these factors were not included in the periphyton model. See explanations in the following sections.

Two models, to predict nuisance instream plant growth, were developed as Bayesian Belief Networks in Netica software and the interfaces of each are shown below (Figure 7-2, Figure 7-3). A description of the variables (their value categories and associated probabilities) used in each model and discussion of the literature from which they are derived are outlined in following section. There are some model variables that are not routinely measured by Regional Councils (e.g., light at bed) so we have provided a relatively simple means to estimate these as part of the model documentation (e.g., light at bed as a function of incident lighting (taking into account riparian and topographic shade), black disk visibility, absorbance and stream depth).

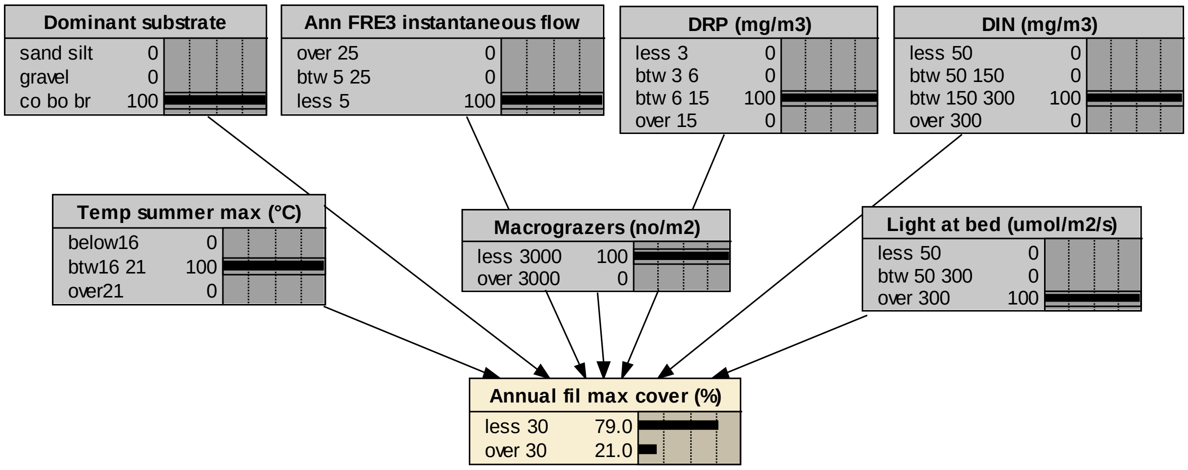

Figure 7-2: Interface of the Bayesian Belief Network of factors influencing the probability of periphyton Annual Filamentous Maximum (AFM) cover exceeding the MfE (2000) 30% guideline at least once a year with monthly observations. Temp (summer max, °C) = 95th percentile water temperature, Dom substrate = dominant substrate type (co = cobble, bo = boulder, br = bedrock), Light at bed = daily average, DRP = annual mean dissolved reactive phosphorus, DIN = annual mean inorganic N, Ann FRE3 = annual frequency of instantaneous flows greater than 3 times the median, and macro grazers = density of invertebrate macrograzers.

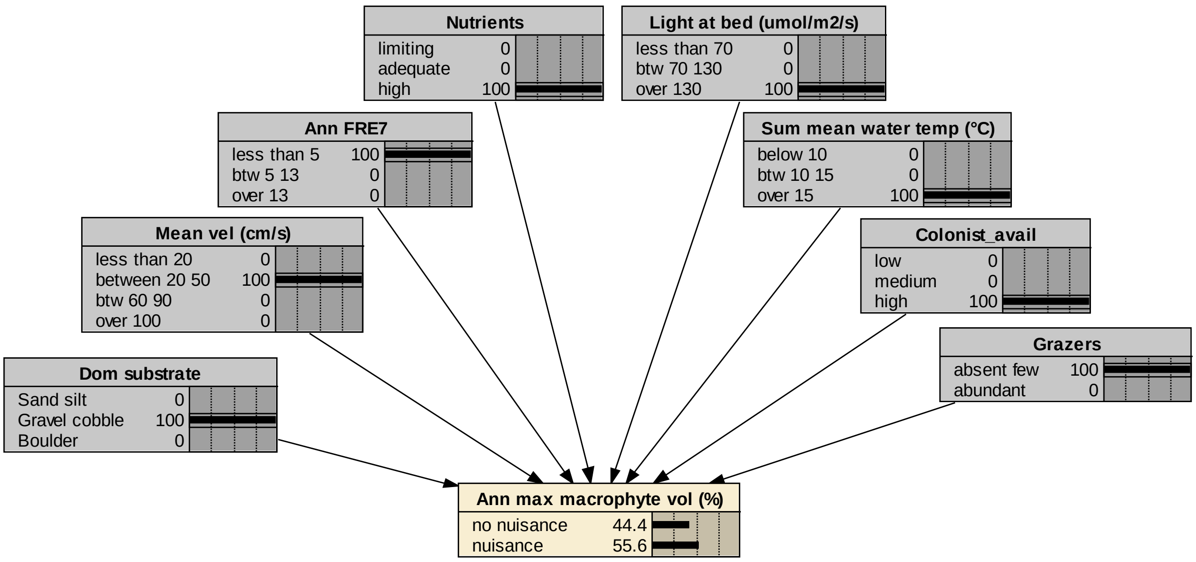

Figure 7-3: Interface of the Bayesian Belief Network of factors influencing the probability of annual maximum macrophyte abundance as volume or cross-sectional area of channel occupied exceeding 50%. Dom substrate = dominant substrate type, Mean vel = mean stream velocity, Ann FRE7 = annual frequency of flows greater than 7 times the median with 14 d filter period, Nutrients = the abundance of dissolved inorganic N and reactive P or sediment N and P (see Table 7-14), Light at bed = daily average, Sum mean water temp = summer time mean water temperature, Colonist_avail = the nuisance risk level associated with the presence of particular macrophyte species (see Tables 7-8 and 7-9) , and Grazers = the qualitative abundance of grazer species (e.g., fish, birds, invertebrates).

To use the models the appropriate state for each variable is selected for the site of interest and the model generates an overall nuisance plant risk rating for that site. The user can also use the model to investigate the influence of management options/scenarios (i.e., the effect of changing the states of one or more of the variables) on the nuisance plant risk rating. For example, if riparian planting were predicted to reduce light at bed from high (daily average PAR > 300 µmol m^{-2} s^{-1}) to low (< 50 µmol m^{-2} s^{-1}), the user could test the influence of this change on the nuisance plant risk rating. These models are essentially a series of linked hypotheses based on current knowledge and can be further refined as more information becomes available. Some more detailed illustrative examples of how the BBN models might be used are provided in Section 7.4. Access to Netica software is required to run the models. Fortunately, the models we have developed are able to be run using the freeware versions of the Netica that can be downloaded at http://www.norsys.com/download.html.

We performed initial testing of the BBN model using the NRWQN periphyton dataset (Quinn and Raaphorst 2009) and the State of Environment monitoring dataset supplied by Northland Regional Council (NRC). The NRC dataset was the only one supplied by regional councils that included values for most of the regulating variables in the models and measures of both periphyton and macrophyte abundance.

The BBN models that we have developed are intended to be broadly applicable across different river types, and are probably best used as a default option when no other more detailed region-specific or site-specific analysis is available or as the initial screening tool in an overall decision-support framework (see Section 7.4).

7.2 Model variable documentation

7.2.1 Light at bed

Introduction and bed light calculation

An adequate amount of photosynthetically available radiation (PAR) is essential for aquatic plant photosynthesis and growth. Lighting levels for instream plants are primarily affected by (1) the amount of light reaching the water surface (influenced by day length, season, and vegetative and topographic shade) and (2) the amount of light that penetrates through the watercolumn to the stream bed. Emergent or floating leaved macrophyte species are clearly less affected by (2) than submerged species, but still require adequate streambed lighting to initiate growth/establishment on the streambed. Measurement of the amount of light reaching the stream bed is the most direct way to assess instream light availability for communities dominated by submerged species and effectively integrates the two factors described above. However, measuring this is logistically challenging so that streambed lighting is usually calculated as the product of incident PAR, a shade factor, the vertical diffuse light attenuation coefficient (K_d) of the water and the average stream depth (see instruction box below).

Light control of macrophytes

Within the literature there is only limited information linking instream macrophyte abundance to light levels at the stream bed and most of this relates to abundance as cover not volume. Julian et al. (2011) found that macrophyte cover during summer in the nutrient-rich Big Spring Creek in Wisconsin increased linearly from 0 to 80% cover as daily average streambed PAR increased from 45 to c.170 µmol m^{-2} s^{-1}, but did not increase with further light increase to 300 µmol m^{-2} s^{-1}. Submerged macrophyte cover exceeded 50% at benthic PAR levels over ~130 µmol m^{-2} s^{-1}. Submerged macrophytes are considered to require at least 2 and up to 29% of surface-ambient light for growth, depending on species (Lacoul and Freedman 2006). Sand-Jensen and Borum (1991) estimated the minimum average light requirements for macrophyte persistence to be around 45-90 µmol m^{-2} s^{-1}. However, the compensation point for a common New Zealand stream macrophyte, *Elodea canadensis*, is considered to be around 30 µmol m^{-2} s^{-1} (Brown et al. 1974). The compensation point is the light intensity where the rate of photosynthesis equals the rate of respiration and plants cannot survive where light levels are consistently below this point. We have therefore assigned a growth-limiting threshold close to the bottom of the above range (Table 7-1).

Table 7-1: Light at bed categories for the macrophyte BBN.

Light at bed (µmol PAR m^{-2} s^{-1}) [a]	Probability of nuisance growth
>150	0.95
50-150	0.50
<50	0.10

[a] mean daily radiation.

Estimating light at the stream bed

To determine light at bed directly requires the use of an underwater PAR (photosynthetically available radiation) sensor (e.g., Wetlabs PARSB sensor $US5700). Few Regional Councils probably have access to this equipment for SoE monitoring. However, we suggest that it is possible to estimate light at bed from a selection of more readily measurable parameters; i.e., stream depth, black disk clarity, absorption coefficient (G_{340}), stream shading level, and incident radiation (available from a local climate station, see http://cliflo.niwa.co.nz/).

The procedure to estimate light at bed is as follows (note that all logs are to base 10):

1. Calculate the diffuse light attenuation coefficient (K_d) from black disk clarity (Y_{SD}) and the absorption coefficient (G_{340}) using Equation 1 (Davies-Colley & Nagels 2008).

[1] $\log(K_d) = 0.2145*\log(G_{340})-0.5034*\log(Y_{SD})-0.0649$

NB: $G_{340} = 2.303\ (A_{340}$ - App. $A_{740})$/cuvette path length (m; usually 0.040m)

App. $A_{740} = A_{740} \times 2.176471$ (Davies-Colley and Vant 1987)

2. Calculate the amount of light (radiation) reaching the streambed without accounting for any shading (L, MJ m^{-2}) from the incident radiation (R, MJ $m^{-2}\ d^{-1}$), attenuation (K_d) and depth (d, metre) using Equation 2.

[2] $L=R*e^{-Kd*d}$

3. Calculate the amount of light reaching the streambed accounting for the amount of riparian shade (L_s, MJ m^{-2}) using Equation 3. To include shading caused by riparian vegetation, the percentage shade (S, %) is used.

[3] $L_s=L*0.01*(100-S)$

[4] To convert L_s from MJ $m^{-2}\ d^{-1}$ to µmol $m^{-2}\ s^{-1}$ multiply by 53.2.

Example: A stream reach has a black disk clarity of 1.0m, an absorption coefficient (G_{340}) of 7.2, a depth of 0.5m, incident radiation of 13.2 MJ $m^{-2}\ d^{-1}$ and shading of 50%.

[1] $\log(K_d) = 0.2145*\log(7.2)-0.5034*\log(1.0)-0.0649$

$\log(K_d) = 0.1839-0.0-0.0649$

$\log(K_d) = 0.1190$

$K_d = \text{log inv}(0.1190) = 10^{0.1190}$

$K_d = 1.31$

[2] $L=13.2*e^{-1.31*0.5}$

$L=13.2*e^{-0.655}$

$L=13.2*0.519$

$L=6.86$ MJ $m^{-2}\ d^{-1}$

[3] $L_s=L*0.01*(100-S)$

$L_s=6.86*0.01*(100-50)$

$L_s=3.434$ MJ $m^{-2}\ d^{-1}$

[4] $L_s=3.434*53.2$

$L_s=182$ µmol $m^{-2}\ s^{-1}$

NB. K_d can also be calculated from turbidity and G_{340} using Equation 2 in Davies-Colley and Nagels (2008). If black disk clarity (or turbidity), absorbance and/or stream depth data are not available, light at bed could be estimated without accounting for any attenuation through the watercolumn. To do this begin at equation 3 and assume that $L=R$.

Light control of periphyton blooms

Periphyton production rates, for communities adapted to high light, are generally thought to be light-saturated at benthic PAR levels of between 100-400 µmol m^{-2} s^{-1}. Results from New Zealand West Coast Rivers (Davies-Colley et al. 1992) and Waikato streams (Quinn et al. 1997) support this range for light saturation. Sites with average <300 µmol m^{-2} s^{-1} amongst the 65 NRWQN rivers (Figure 3-6) almost always had <30% average annual maximum filamentous cover. High light levels are also predicted to influence periphyton community composition towards types that develop higher biomass, as follows: diatoms <50 µmol m^{-2} s^{-1}; diatoms plus some blue-greens and greens at 50-100 µmol m^{-2} s^{-1}; and greens at >100 µmol m^{-2} s^{-1} (Steinman et al.1989).

Shade experiment studies in streamside channels adjacent to a Waikato hill stream report that at 60% or higher shade (24h average PAR < c.200 µmol PAR m^{-2} s^{-1}) periphyton was almost always below 30 mg chl *a* m^{-2}, whereas 2 of 3 replicate unshaded channels (24h average PAR = 500 µmol PAR m^{-2} s^{-1}) had occasional blooms (50-170 mg chl *a* m^{-2}) during summer (Quinn et al. 1997).

Surveys of streams of the Coromandel (Boothroyd et al. 2004) and across the North Island (Davies-Colley and Quinn 1998) found correlations between mean periphyton biomass in runs and lighting at the stream and bank level. Coromandel streams with bank level shade less than 60% averaged 50 mg chl *a* m^{-2} (max = 125 mg chl *a* m^{-2}, n=8), whereas those with greater shade (average = 89%, corresponding to 24 h average PAR of c. 50 µmol PAR m^{-2} s^{-1}) averaged 11 mg chl *a* m^{-2} (max = 35 mg chl *a* m^{-2}, n=14) (Boothroyd et al. 2004). Comparisons across North Island streams indicated regional differences in relationships between lighting and periphyton biomass, likely reflecting differences in nutrients, flow regimes, substrates and grazing, but periphyton biomass of >50 mg m^{-2} was typically associated with <80% shade at the streambed (Davies-Colley and Quinn 1998). All of these studies were carried out in clear, shallow, streams where little light attenuation was expected between the surface and the streambed.

Shade decreased with riparian deforestation by pastoral land use or clearfell logging and, with increasing channel width within late rotation pine plantations and native forest (Davies-Colley and Quinn 1998). These and other unpublished observations indicate that established riparian forests provide >70% shade at channel widths up to 10-15m whereas the increasing canopy gap at greater channel widths results in relatively low effective shade in wider channels. Trees with broad spreading or weeping shape (e.g., willows) provide more effective shade at greater channel widths than those with conical (e.g., pines) or columnar shape (e.g., poplars) and east-west orientated channels are better shaded than north-south channels.

From this review we propose the streambed lighting states and weightings for influence on the risk of nuisance periphyton blooms shown in Table 7-2.

Table 7-2: Light at bed categories for the periphyton BBN.

Light at bed (μmol PAR m^{-2} s^{-1}) [a]	Probability of nuisance growth
>300	0.95
50-300	0.65
<50	0.10

[a] average daily radiation.

7.2.2 Flow velocity

Flow velocity is used only in the macrophyte BBN. For the periphyton BBN we have not used a flow velocity variable. Nuisance periphyton growths occur across a wide range of flow velocities although community composition will differ. As flow velocities increase across the normal range found in streams (0 to 1 m s^{-1}), long filamentous algae decrease, mucilaginous diatom mats increase and stalked diatoms/short filamentous algae peak at around 0.5 m s^{-1} (MfE 2000). Velocity effects on periphyton biomass involve complex interactions with nutrients and changes in species composition that influence the balance between the positive effects of increased velocity on mass transfer of nutrients and the negative effects of increased shear stress (Horner and Welch 1981; Biggs 1996; Biggs et al. 1998). Hence we have not attempted to include velocity effects in our general models.

Several studies have examined relationships between average flow velocities and macrophyte abundance. In constant flow streams, Henriques (1987) found that summer time macrophyte channel volume was generally <50% at average flow velocities >0.35-0.40 m s^{-1} and <10% at velocities >0.9 m s^{-1}. Riis & Biggs (2003) studying 15 New Zealand streams found increasing macrophyte cover as velocities increased from 0 to 0.3 m s^{-1} and a reduction in cover at velocities >0.4 m s^{-1}. Chambers et al. (1991), studying macrophyte-flow relationships in the Bow River (Canada), found that current velocities >1 m s^{-1} inhibited macrophyte growth. Their results also indicated that flow velocities greater than 0.7-0.9 m s^{-1} generally prevented the development of macrophyte biomass >100 g m^{-2} and that flow velocities above 0.2-0.5 m s^{-1} generally prevented biomass development >500 g m^{-2}. In an experimental stream study, Chapman et al. (1974) found that the optimal current velocity for *Ceratophyllum demersum* growth was around 0.5 m s^{-1}. Considering all of the above information, the categories and probabilities we have assigned to mean current velocity for macrophytes are presented in Table 7-3 below

Table 7-3: Mean flow velocity categories for the macrophyte BBN.

Mean flow velocity (m s^{-1})	Probability of nuisance growth
<0.20	0.70
0.20-0.49	0.95
0.50-0.90	0.30
>0.90	0.05

7.2.3 Flood magnitude and frequency

Flood magnitude and frequency influence development of both macrophytes and periphyton by increasing the drag stresses on plants, mobilising sand and fine particle bedload that scours algae and, at particularly high flows, mobilising the dominant bed substrate.

For macrophytes, Haslam (1978) found that a flood 2.5 times the normal flow removed some of the dominant macrophytes in a stream reach but a flood 4 times the normal flow removed half of the dominant macrophytes and most of the small plants. New Zealand research in 13 South Island, predominantly unshaded gravel-bed, streams (Riis and Biggs 2003) has shown that macrophyte vegetation is absent from streams with >13 high-flow disturbances per year (i.e., annual frequency of floods greater than 7 times the median flow with two-week interval between consecutive events; AnnFRE7). This analysis also showed that macrophyte cover was generally <50% in streams with an AnnFRE7 of around 5 or more. However, macrophyte volume in these study streams was ≤40%, below our provisional guideline for nuisance macrophyte abundance. This information was used to inform the macrophyte BBN flood disturbance variable (AnnFRE7) states and influences in Table 7-4. However, we consider that further research is required to examine these relationships in soft-bottom lowland streams where macrophytes often attain a much higher abundance than elsewhere.

Table 7-4: Annual frequency of floods greater than seven times the median flow (AnnFRE7) with 14 d filter period categories for the macrophyte BBN.

AnnFRE7	Probability of nuisance macrophyte growth
<5	0.95
5-13	0.30
>13	0.05

For periphyton, limited published information is available so categories and probabilities are based on our best judgement and inspection of the NRWQN data. Clausen and Biggs (1997) regarded the frequency of floods greater than three times the median flow (FRE3, based on daily mean flows) as the most ecologically useful flow variable in New Zealand streams and found that periphyton biomass decreased in response to increasing FRE3. Work in experimental channels in the Waitaki River suggested that proliferations of periphyton were absent when there were greater than 26 floods per year (3 times existing flow) but could occur when there were <13 floods per year (Rutledge et al. 1992).

We considered that the summer time frequency of floods greater than 3 times the median flow (SumFRE3) may be the best flow variable to use to model flow disturbance effects on nuisance periphyton growths, but we currently lack available data to evaluate this metric using the NRWQN database. We also contend that using a FRE3 derived from the instantaneous peak daily flows (operationally defined as the daily hourly maximum, giving $FRE3_{inst}$), rather than the mean daily flow used by Clausen and Biggs (2003) and the *New Zealand Periphyton Guideline*, is likely to be more relevant to periphyton scour. $FRE3_{inst}$ was more strongly correlated with AFM than the conventional FRE3 based on daily mean flow in the NRWQN database (see section 6.2 above). Consequently, the AFM BBN uses annual $FRE3_{Inst}$ ($AnnFRE3_{Inst}$, no filter period) as the flow variability predictor (Table 7-5).

Sites with average >25 flow events of >3 times the median flow ($AnnFRE3_{Inst}$) almost always (2 exceptions, Waitara and Manawatu at Opiki) had <30% average annual maximum filamentous cover amongst 65 NRWQN rivers (Figure 6-1).

Table 7-5: Annual instantaneous peak FRE3 categories for the periphyton BBN.

$AnnFRE3_{Inst}$	Probability of nuisance growth
<5	1.00
5-25	0.70
>25	0.20

7.2.4 Substrate

The bed substrate provides the attachment surface for periphyton development and both the rooting habitat and a nutrient source for macrophytes. Thus its character and stability has strong influences on the development of both classes of streambed vegetation.

Riis and Biggs (2003) studied the substrate preferences of several New Zealand stream macrophyte species. Of the species studied, those capable of forming nuisance growths (*Elodea canadensis*, *Myriophyllum triphyllum, Ranunculus trichophyllus*) were found to be most abundant on silt, sand and small gravel substrates. This is consistent with our observations of nuisance macrophyte prevalence in streams. These observations inform the macrophyte BBN influence Table 7-6.

Table 7-6: Substrate categories for the macrophyte BBN.

Substrate	Probability of nuisance growth
Clay-silt-sand	0.95
Gravel-cobble	0.50
Boulder-bedrock	0.05

Nuisance periphyton growths are most common where stream substrates are stable and consist of larger substrata (i.e., gravels, cobbles and boulders) (see MfE 2000). Streams with fine sediment substrata are generally a less favourable habitat for periphyton; although growths can sometimes develop in these streams on alternative more stable attachment surfaces (e.g., instream wood or macrophyte beds) or where flows are very stable. Sites with sandy or silty substrates (i.e., a substrate index value of ~4.8) almost always (1 exception) had <30% average annual filamentous maximum cover amongst 65 NRWQN rivers (Figure 6-1). These observations inform the influence Table 7-7.

Table 7-7: Substrate categories for the periphyton BBN.

Substrate	Probability of nuisance growth
Clay-silt-sand	0.10
Gravel	0.70
Cobble-boulder-bedrock	1.00

7.2.5 Colonist availability

Some macrophyte species commonly form nuisance growths in New Zealand streams and rivers while others do not. Below, we have categorised New Zealand species according to their potential to form nuisance growths under favourable growing conditions (Table 7-8) Most of the high and medium risk colonist species are introduced species, but not all. We have then assigned 'probabilities of nuisance growths developing', to the three nuisance colonist availability categories (Table 7-9). Selection of the appropriate category is based on: at least one of the species listed being present at a site and, the highest colonist availability risk level that is represented by the species present.

Table 7-8: Nuisance colonist availability categories and species assigned to each category for the macrophyte BBN.

Nuisance colonist availability	Species present include:
High	*Ceratophyllum demersum* *Lagarosiphon major* *Egeria densa* *Potamogeton crispus* *Alternanthera philoxeroides* *Myriophyllum aquaticum*
Medium	*Elodea canadensis* *Nitella hookeri* *Myriophyllum triphyllum* *Callitriche stagnalis* *Ranunculus trichophyllus* *Nasturtium spp.* *Apium nodiflorum* *Glyceria spp.* *Otelia ovalifolia* *Azolla spp.* *Lemna spp.*
Low	*Nitella stuartii* *Bryophytes* *Glossostigma* spp. *Chara* spp. *Potamogeton ochreatus* *Potamogeton cheesmanii* *Myriophyllum propinquum*

Table 7-9: Nuisance colonist availability categories for the macrophyte BBN.

Nuisance colonist availability	Probability of nuisance growth
High	0.90
Medium	0.50
Low	0.10

7.2.6 Grazers

Just as the density of cows in a field can control pasture biomass, the density of grazers can influence instream plant biomass. There are relatively few grazers of macrophytes in New Zealand streams and rivers and it is unlikely that grazing contributes significantly to biomass control in most instances. Consumers of freshwater macrophytes include rudd (*Scardinius erythrophthalamus*), koura (freshwater crayfish) and waterfowl (e.g., swans, coots) (Carpenter and Lodge 1986, Lodge 1991) but many of these species are not common in our streams and rivers. Most freshwater invertebrate grazers consume epiphyton on macrophyte leaves, although some will graze directly on macrophyte tissues (e.g., species of *Decapoda*, *Coleoptera*, *Gastropoda*, *Trichopteran* and *Lepidopteran* larvae) (Lodge 1991, Elger et al. 2004). Macrophyte-consuming snails found in New Zealand freshwaters include *Lymnaea stagnalis* (Gastropoda) which is known to consume more than 30 macrophyte species, including *Ceratophyllum demersum*, *Elodea canadensis*, *Potamogeton crispus* and *Lemna minor* (Elger et al. 2004), which are present in New Zealand. The native New Zealand mud snail (*Potamopyrgus antipodarum*), which is common in lowland streams, generally consumes algae and detritus rather than live macrophyte tissues. From this review, we propose relatively low grazer control influence on macrophytes (Table 7-10). Since no quantitative thresholds were found in the literature to link macrophyte and grazer abundance we can only suggest broad qualitative categories for this parameter in the macrophyte BBN at this stage.

Table 7-10: Grazer categories for the macrophyte BBN.

Grazer abundance	Probability of nuisance growth
Low (few or absent)	0.90
High (abundant)	0.40

The main grazers of periphyton are stream invertebrates (Winterbourn 2000). It is likely that invertebrates harvest periphyton both as food and clearance to maintain favourable near-bed hydraulic conditions for filter feeding (e.g., net-spinning caddisflies) (Pan & Lowe 1995). Studies have shown that invertebrate grazing can alter periphyton composition and limit biomass (e.g., Jacoby 1987; Feminella et al. 1989; Holomuzki et al. 2006; Holomuzki and Biggs 2006). Anderson et al. (1999) suggested that a caddisfly larvae grazer biomass >1500 mg m^{-2} would probably prevent the development of nuisance periphyton, including filamentous growths, even in nutrient enriched streams. In New Zealand, Welch et al. (1992) found that invertebrate grazer densities of >3000 m^{-2} maintained low summer periphyton biomass regardless of nutrient concentration in 7 NZ streams. However, high grazer densities such as this may be relatively uncommon; Quinn and Hickey (1990) found that only 26% of 88 NZ rivers studied had grazer densities above this threshold. These observations were used to inform the grazer influence Table 7-11.

Table 7-11: Grazer categories for the periphyton BBN.

Invertebrate grazer abundance	Probability of nuisance growth
Low (<3000 m^{-2} or <1500 mg m^{-2})	0.60
High (>3000 m^{-2} or >1500 mg m^{-2})	0.40

7.2.7 Temperature

Macrophyte growth and biomass generally increase in response to temperature over the water temperature range of most New Zealand streams and rivers. Barko et al. (1984) found that the biomass of submersed macrophytes (*Elodea canadensis*, *Potamogeton nodosus* and *Vallisneria americana*) increased steadily with increasing water temperatures from 12 to 32°C. Madsen and Brix (1997) found that growth rates of *Elodea canadensis* and *Ranunculus aqualitis* increased with a Q_{10} (rate of increase for every 10°C rise in temperature) of 2.3 to 3.5 between temperatures of 5 and 15°C. They also found that growth of *Elodea* was virtually halted at a temperature of 5°C. Most macrophyte species require ambient water temperature to reach at least 10°C during the growing season to survive and most species are killed or rendered dormant by temperatures <3°C or >45°C (Lacoul and Freedman 2006). This review formed the basis for the temperature categories in the macrophyte BBN (Table 7-12).

Table 7-12: Summer[a] mean water temperature categories for the macrophyte BBN.

Water temperature (°C)	Probability of nuisance growth
>15	0.90
10-15	0.50
<10	0.10

[a] December to March inclusive

Temperature influences periphyton biomass both directly, by increasing algal growth rates (the Q_{10} for most algae is approximately 2 (Davison 1991), although Morin et al. (1999) found gross primary production Q_{10} to be 2.5 for stream periphyton) and indirectly through top-down effects on fish predators on grazer abundance and grazing rates (e.g., Rutherford et al. 2000; Kishi et al. 2005). These thermal influences favour increased periphyton biomass development with increasing temperature. In the NRWQN database sites with 95th percentile temperature (i.e., summer maximum) <16ºC almost always (1 exception) had <30% average annual maximum filamentous cover (Figure 6-1). From this review we have derived the temperature categories for periphyton BBN (Table 7-13).

Table 7-13: 95th percentile water temperature categories for the periphyton BBN.

Water temperature (°C)	Probability of nuisance growth
>21	1.00
16-21	0.60
<16	0.10

7.2.8 Nutrients

Plants require a variety of nutrients in addition to carbon to support protein synthesis and cellular functioning. Requirements for nitrogen and phosphorus are particularly crucial and a deficit in the supply of one of these often limits plant biomass development. Many other elements and vitamins are also important and can be crucial for some plant groups (e.g., silica for diatoms and molybdenum for cyanobacteria) but these are usually thought to be sufficiently available to not limit growth.

Nuisance growths of aquatic macrophytes are most common in nutrient-rich lowland streams (Haslam 1978). Most macrophyte species can acquire nutrients from both the water-column and sediments (e.g., Carr et al. 1997), so they can still grow well even when water-column nutrient concentrations are relatively low. However, macrophyte species lacking roots, such as floating species or *Ceratophyllum demersum*, are dependant almost entirely on foliar uptake of nutrients from the water column (Denny 1972). Some macrophyte species are known to prefer conditions rich in specific nutrients or elements. For example, *Callitriche stagnalis* and *Ceratophyllum demersum* prefer high nitrogen conditions, *Elodea canadensis* requires high-available iron, and *Ranunculus trichophyllus* has an affinity for calcium (Lacoul and Freedman 2006). However, here we consider only the key nutrients, nitrogen and phosphorus, as these are generally regarded as having the most potential for limiting macrophyte production in aquatic ecosystems (Barko et al. 1991).

Half-saturation constants, concentrations supporting uptake at half the maximum rate, can be used to indicate potentially limiting concentrations for nutrients. For submerged macrophytes half-saturation constants are considered to range from 75-150 µM N (1.0-2.1 g m^{-3}) and 5-15 µM P (0.16-0.48 g m^{-3}) (Murray et al. 1992). However, these relatively high concentrations are at odds with observations that, in lake systems supporting macrophytes, surface water DRP concentrations rarely exceed 10 mg m^{-3} and at concentrations of 20 mg m^{-3} macrophytes start to be excluded as a result of light attenuation associated with phytoplankton growth (Barko et al. 1991). Nevertheless, in cases of extreme infertility, i.e., oligotrophic systems, where both water column and sediment nutrient levels are low, growth may be limited by nutrient availability, as found for macrophytes in a Danish lake where sediment nutrient contents were very low (~0.02%N and 0.005%P; Christiansen et al. 1985, Barko et al. 1991). However, lotic sediment nutrient concentrations, particularly in lowland areas, may rarely be this low, especially for phosphorus. In Britain, nutrient concentrations in the sediments of lowland rivers of moderate to high trophic status ranged from 0.02-0.52%N and 0.02-0.22%P (Clarke and Wharton 2001).

Work in both lakes and rivers suggests that macrophytes are more prone to limitation by nitrogen (particularly NH_4^+), than phosphorus because pools of exchangeable N in sediments are smaller and more rapidly depleted than those of phosphorus (Barko et al. 1991, Clarke and Wharton 2001). Feijoo et al. (1996) found a positive correlation between biomass of the submerged macrophyte *Egeria densa* and nitrogen concentrations (water column NH_4^+ and sediment TN) in 20 Argentinian streams. In this study sediment TN concentrations ranged from 0.03-0.27% N and water column NH_4^+ concentrations from 0-0.7 g N m^{-3}, although NO_3^- concentrations (1.8-8.3 g N m^{-3}), and thus DIN, were much higher. In the Bow River, aquatic macrophyte biomass decreased substantially following a reduction in watercolumn nitrogen loading to <1.0 g m^{-3} DIN (0.11-0.28 g m^{-3} NH_4-N and 0.47-0.81 g m^{-3} NO_x-N (Soziak 2002). Although the magnitude of plant reduction was not specifically stated, it appears that the macrophyte biomass at most sites was around 500-1000 g DW m^{-2} or more, prior to nitrogen removal, which then subsequently declined to levels <500 g DW m^{-2}.

Overall, information on water and sediment nutrient concentrations likely to limit the growth of nuisance macrophytes is very limited and relationships are complicated by the plants ability to obtain nutrients from both water and sediment sources in most cases. The categories assigned in the nutrient influence table for the macrophyte BBN (Table 7-14) are thus based on our best professional judgement combined with the findings of studies discussed above.

Table 7-14: Annual mean dissolved inorganic and total sediment nutrient categories for the macrophyte BBN. A category can be selected based on only watercolumn or sediment concentrations if only one is available. If one of the nutrients (e.g., DIN) is in the high category and the other is in the adequate category (e.g., DRP) then select the category corresponding to the lowest concentration. If either nutrient is in the limiting category then this category should be selected as growth is likely to be constrained by this nutrient.

Category	Watercolumn nutrients (mg m^{-3})	Sediment nutrients (%DW)	Probability of nuisance growth
High	DIN >1000 and/or DRP >100	TN >2 and/or TP >0.2	0.90
Adequate	DIN 100-1000 and/or DRP 10-100	TN 0.1-2 and/or TP 0.01-0.2	0.70
Limiting	DIN <100 or DRP <10	TN <0.1 or TP <0.01	0.30

For periphyton, much of the international literature is focused on P thresholds as this is thought to be the nutrient most commonly limiting growth in freshwaters. However, the USEPA (2000) provides a useful summary table of nutrient and periphyton criteria to prevent instream nuisance conditions and water quality degradation that includes recommendations for both nitrogen and phosphorus (Table 7-15). Some of these examples are discussed further below.

Table 7-15: Nutrient and algal biomass criteria recommended to prevent nuisance conditions and water quality degradation in streams. These are based on either nutrient-chlorophyll a relationships or preventing risks to stream impairment as indicated.

TN mg m^{-3}	TP mg m^{-3}	DIN mg m^{-3}	DRP mg m^{-3}	Chlorophyll a mg m^{-2}	Impairment risk	Source
				100-200	nuisance growth	Welch et al. 1987, 1989.
275-650	38-90			100-200	nuisance growth	Dodds et al. 1997.
1500	75			200	eutrophy	Dodds et al. 1998.
300	20			150	nuisance growth	Clark Fork River Tri-State Council, MT.
	20				*Cladophora* nuisance growth	Chetelat et al. 1999.
	10-20				*Cladophora* nuisance growth	Stevenson, unpubl. Data.
		430	60		eutrophy	UK Environment Agency 1988.
		100[1]	10[1]	200	nuisance growth	Biggs 2000.
		25	3	100	reduced invertebrate diversity	Nordin 1985.
			15	100	nuisance growth	Quinn 1991.
		1000	10[2]	~100	eutrophy	Sosiak pers. comm.

[1] 30-day biomass accrual time.

[2] Total Dissolved P.

In the Bow River, Soziak (2002) found that periphyton biomass in the lower river declined following controls on phosphorus discharge which resulted in TDP concentrations <10 mg m^{-3} TDP. Using regression analysis he identified a threshold for nuisance periphyton growth (>150 mg m^{-2} chl *a*) of 6.4 mg m^{-3} TDP (equivalent to ~18 mg m^{-3} TP, 95% confidence interval 1.9-7.6 mg m^{-3} TDP) . Controls on nitrogen were also later implemented in this river but reductions in periphyton occurred prior to this. In two lowland United Kingdom rivers, the concentration below which phosphorus began to limit periphyton accrual rate was 50-90 mg m^{-3} DRP (Bowes et al. 2007, Bowes et al. 2010) with biomass reduced by 60% (to 120-240 mg chl *a* m^{-2}) at <40 mg m^{-3} DRP in one river (Bowes et al. 2007). Mainstone and Parr (2002) developed a eutrophication classification system for rivers in England and Wales and suggested that 50 mg m^{-3} DRP was the concentration that P was likely to become limiting throughout the year. The United Kingdom's Environment Protection Agency has a target of 60 mg m^{-3} DRP for chalk streams. A desktop study by Dodds et al. (1997) suggested that periphyton biomass was likely to be kept below 100 mg m^{-2} chl *a* at a P concentration <30 mg m^{-3} DRP. The Dodds et al. (1997) study results also suggested that maximum benthic chlorophyll *a* would likely exceed 200 mg m^{-2} at 90 mg m^{-3} TP and exceed 50 mg m^{-2} at 55 mg m^{-3} TP. The range of target concentrations from individual studies thus varies widely, and for DRP is considered to be from <3 to >100 mg m^{-3} (Scrimgeour and Chambers 1997, Matlock et al. 1999). Bothwell (1988) showed that growth rate saturation in benthic algae occurs under ideal conditions at a concentration of only 0.3-0.6 mg m^{-3} DRP. However, since a developing benthic mat will constrain eddy and molecular diffusion of nutrients, and hence limit total biomass development by reducing growth of cells deeper within the mat (Pringle 1990), a higher concentration will be required to reach maximum algal biomass (i.e., 8-25 mg m^{-3} DRP, Horner et al. 1983, 1990; 30-50 mg m^{-3} DRP, Bothwell 1989). Nitrogen limitation in benthic algae has been reported at concentrations of 55 to 100 mg m^{-3} NO_3-N (Borchardt 1996).

In New Zealand, the limited information available suggests that nutrient criteria should probably be at the lower end of the range reported in the international literature. The *New Zealand Periphyton Guideline* (MfE 2000) suggests that annual average concentrations ranging from <10 to <295 mg m^{-3} DIN and <1 to <26 mg m^{-3} DRP are required to control periphyton biomass (as filamentous algae) below 120 mg chl *a* m^{-2}, with accrual times (i.e., interval between significant flushing flows) ranging from 20-100 days in predominantly South Island cobble-bed rivers/streams. Examination of relationships between nuisance periphyton cover and nutrients in the New Zealand NRWQN dataset (Figure 6-1), which covers a broader range of locations, suggests the following general nutrient states and associated probabilities of contributing to nuisance periphyton growths if all other factors are optimal (Table 7-16).

Table 7-16: **Annual mean dissolved inorganic nutrient categories for the periphyton BBN.** If both nutrients fall within different categories then select the category corresponding to the lowest concentration.

Category	Watercolumn nutrients (mg m^{-3})	Probability of nuisance growth
High	DIN >300 and/or DRP >15	1.00
Moderate	DIN 150-300 and/or DRP 6-15	0.70
Adequate	DIN 50-150 and/or DRP 3-6	0.50
Limiting	DIN <50 or DRP <3	0.30

7.3 Model testing

7.3.1. Introduction

We used the NRWQN database as a national scale test of the periphyton BBN and the Northland Regional Council dataset as a regional scale test of both the periphyton and macrophyte BBNs. Most of the regional council datasets did not contain information for a sufficient number of the BBN variables for testing (see Appendix F). The Northland Regional Council dataset was the most comprehensive for this purpose.

7.3.2 National scale testing

The 1990-2006 NRWQN data for each site were used to test the periphyton BBN of factors influencing the risk of nuisance filamentous growths. Around 20% of the NRWQN sites periodically experience nuisance filamentous algal growths. They are mostly large, gravel-cobble bed rivers/streams.

The BBN predicted risk of the annual filamentous maximum (AFM) cover exceeding the *New Zealand Periphyton Guideline* guideline of 30% filamentous cover was correlated with the observed AFM at 62 NRWQN sites (r = 0.58, p < 0.0001 for normalised data after excluding sites RO3, AX4 and TU2, that are outliers potentially influenced by highly managed (unusual) flow regimes (see Section 3.6.1 above)). Using an arbitrary low versus high BBN risk cut-off of 12.5%, the model predictions of low risk of nuisance match the AFM at 92% of sites (Figure 7-4, Appendix G). The match of BBN predictions of high AFM risk and NRWQN AFM observations (70% correct) are better than expected by chance (50%), but the performance evaluation was limited by the relatively low number of NRWQN sites that typically have nuisance annual maximum periphyton cover.

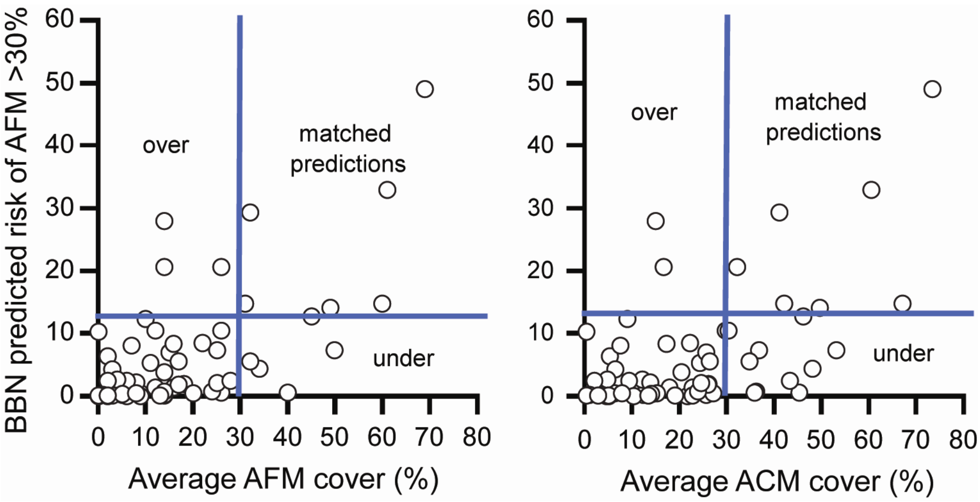

Figure 7-4: Comparison of observed average percentage annual filamentous maximum algal cover (AFM) and observed average annual composite maximum algal cover (ACM) with the BBN predictions of the risk that AFM exceeds the *New Zealand Periphyton Guideline* aesthetic nuisance guideline.

Applying the BBN model developed to predict AFM to the prediction of annual composite maximum (ACM) cover (i.e., filamentous cover + 0.5 x mat cover), with the same cut-offs and 3 site exclusions as above, was slightly less successful than for AFM (overall correct classifications = 82%, c.f. 86% for AFM prediction, Figure 7-4).

It is likely that the prediction success could be improved by increasing the number of states within the BBN variables and refining the ecological relevance of the predictors (e.g., there may be better nutrient concentration and flow variability/accrual period metrics than used in the BBN). BBN testing and refinement with a larger data set involving a greater range of environmental conditions is desirable. Nevertheless, the evaluation indicates that the filamentous algal BBN risk model can be used by managers as an initial screening tool for evaluating the potential effects of activities such as reduction or increase in nutrient concentrations, light (e.g., by managing riparian shade) or flood frequency (e.g., by flushing flow management) (for examples, see Section 7.4).

7.3.3 Regional scale testing

The periphyton and macrophyte BBNs were also tested on the dataset supplied by Northland Regional Council. Further details and limitations of this dataset and full testing results are outlined in Appendix H.

Test results showed that the BBN correctly predicted nuisance plant status at most sites. The macrophyte BBN correctly predicted the status of 84% of the 31 monitored sites. Mispredictions were evident at 5 sites; nuisance macrophyte status was underestimated in four instances and overestimated in one instance. Although these results suggest that the macrophyte BBN has performed well, we acknowledge that the data used for the testing comes from a limited, and less than ideal, dataset (i.e., some parameters infrequently measured) that has been summarised by us. This model requires further more rigorous testing with more comprehensive datasets in the future. The periphyton BBN correctly predicted the status of only 55% of the sites. However in all but one case the BBN overpredicted the occurrence of nuisance growths. Of the 10 sites where nuisance growths were observed, only one was not predicted by the BBN. Overall, the testing results with Northland Regional Council are encouraging given the limitations of the test dataset and suggest that the models will identify, in most instances, those sites where nuisance instream plant growths are likely to occur.

7.4 Examples of BBN model use

The BBNs are intended for use as a risk assessment tool that takes into account all the influences on instream periphyton or macrophyte growth, not just nutrients. The intention of this report was to focus on the effects of nutrients on instream plant growths but we stress that it is important for the effects of other regulating variables to be accounted for in modelling approaches.

Examples of potential uses are:

7.4.1 Hydrodam evaluation

Scenario: A dam is proposed on a river for hydroelectric power generation.

The periphyton BBN could be used to assess downstream changes in nuisance annual filamentous maximum (AFM) algal cover due to effects on flow variability (which would be reduced), substrate (which may become more coarse), temperature (e.g., may increase or decrease depending on whether the dam outlet if surface or bottom water) and light at the streambed (could increase if the dam lowers the stream depth and increases water clarity due to settling of particulates in the dam).

7.4.2 Water storage for irrigation of agricultural land

Scenario: Options are being explored for a water storage dam to supply an irrigation scheme with several candidate streams for locating the dam. There is concern that the development could increase the risk of nuisance periphyton growth in the mainstem of the river below the dam and the streams draining the irrigated area (from irrigation water "return flows").

The periphyton BBN could be used to inform decisions by indicating the change in risk of annual filamentous maximum (AFM) algal cover exceeding the *New Zealand Periphyton Guideline* value of 30% based on changes at the downstream site in nutrient concentrations (e.g., from CLUES, SPASMO or OVERSEER modelling of changes resulting from irrigation driven land use intensification) and FRE3, assuming that substrate, lighting at the streambed and grazer densities will remain the same. If the sites being considered for possible dam locations differ in flow variability (and downstream effects at the mainstem site of interest), then these effects on FRE3 could be used to scope whether particular locations are more or less likely to increase the risk of downstream filamentous algae problems.

7.4.3 Sewage treatment upgrade

Scenario: Proposals are being evaluated to upgrade a sewage treatment plant and different options will reduce nutrient load to the receiving river by different amounts.

The periphyton BBN could be used to evaluate the likely effects of different downstream nutrient concentrations on the risk of the annual filamentous maximum (AFM) cover exceeding the *New Zealand Periphyton Guideline* for aesthetics of 30%, taking into account other key influences. If periphyton development is limited by a sandy/silty streambed, then the macrophyte BBN should also be utilised to evaluate the risk of nuisance macrophyte abundance exceeding the provisional recreation, flow conveyance and ecological habitat guidelines of 50% of channel cross-sectional area or volume (CAV).

For example, suppose the diversion to land irrigation of sewage that currently discharges to a North Island gravel-bed river is predicted to change the nutrient concentrations at sites downstream where attenuation processes result in a downstream gradient of decreasing nutrient levels. Table 7-17 summarises the current and predicted DRP and DIN concentrations in the river at sites immediately below the sewage discharge and at 20 km and 80 km downstream further downstream. The periphyton BBN predicts that under current nutrient conditions and river physical attributes based on NRWQN site HV2 (i.e., bed light = 550 µmol m^{-2} s^{-1}, $FRE3_{inst}$ = 13.5. macrograzers = 5000 m^{-2}, SI = 5.5 (pebble/small cobble), T95%ile = 23.6°C) there is a high risk (>12.5%) of annual nuisance filamentous blooms occurring both above and at sites to at least 20 km downstream of the WWTP discharge, and a marginal (11%) risk at 80 km downstream. The BBN predicts that the nutrient conditions expected with diversion of sewage still produce a high risk of annual exceedence of the guideline above and immediately below the discharge but this risk drops to 'low' at 20 km downstream, and 'very low' at 80 km downstream (Table 7-17).

Table 7-17: BBN predictions of change in risk on annual maximum periphyton cover from monthly observations exceeding the *New Zealand Periphyton Guideline* for protection of aesthetics in response to changes in nutrient concentration due to sewage diversion from a North Island gravel-bed river.

Site	4 km above WWTP	Below WWTP	20 km below WWTP	80 km below WWTP
Current DRP (mg m^{-3})	10	32	11	8
Diversion DRP (mg m^{-3})	10	7	4	2
Current DIN(mg m^{-3})	900	1000	420	160
Diversion DIN (mg m^{-3})	900	850	400	130
BBN risk of AFM>30% -Current	23%	33%	23%	11%
BBN risk of AFM>30% post-sewage diversion	23%	22%	8%	1%

7.4.4 Riparian shade management:

Scenario: Stream riparian planting is proposed for a range of purposes – what height /density of vegetation is needed to reduce the risk of nuisance filamentous periphyton blooms?

The periphyton BBN could help evaluate whether different riparian management strategies would reduce the risk of the annual filamentous maximum (AFM) algal cover exceeding 30% by prediction of the effects of different levels of shade provided by various riparian planting strategies (e.g., based on WAIORA predictions (Davies-Colley et al. 2009) or local experience) on the light reaching the streambed and stream temperature (e.g., based on Rutherford et al. 1999).

7.4.5 Setting nutrient limits

The BBNs may be used to identify those situations where setting of nutrient limits is inappropriate or of low priority. The BBNs can be used to scope the range of likely nutrient limits in sensitive rivers but other tools (specific to river-type or particular rivers) will be required to define specific thresholds. We have developed two decision support frameworks to guide users through this process (Figure 7-5, Figure 7-6).

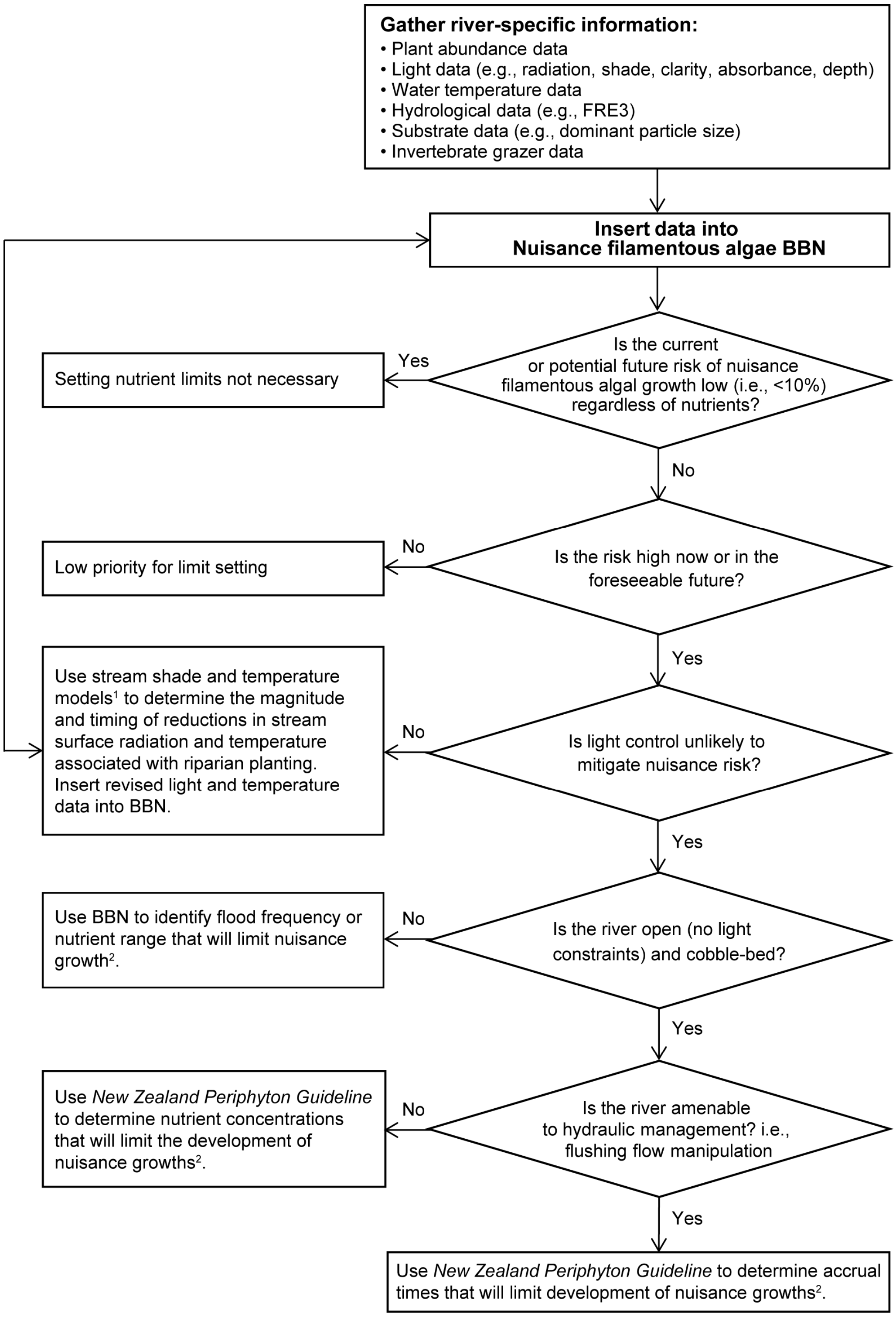

Figure 7-5: Decision-support framework to guide use of nuisance filamentous algae BBN and other existing tools for nutrient limit setting in relation to management of instream plant growth. Note: the *New Zealand Periphyton Guideline* (MfE 2000) nutrient/accrual time criteria apply to nuisance biomass thresholds for ecological impact while the BBN is based on a nuisance cover threshold for aesthetic/recreational purposes. We have assumed that these thresholds are broadly comparable. [1] e.g., WAIORA, figures 6 and 7 Davies-Colley et al. (2009). [2] An alternative approach is to develop river-specific mechanistic or empirical models e.g., Rutherford 2011, Snelder et al. 2011 (See Appendix I for further information).

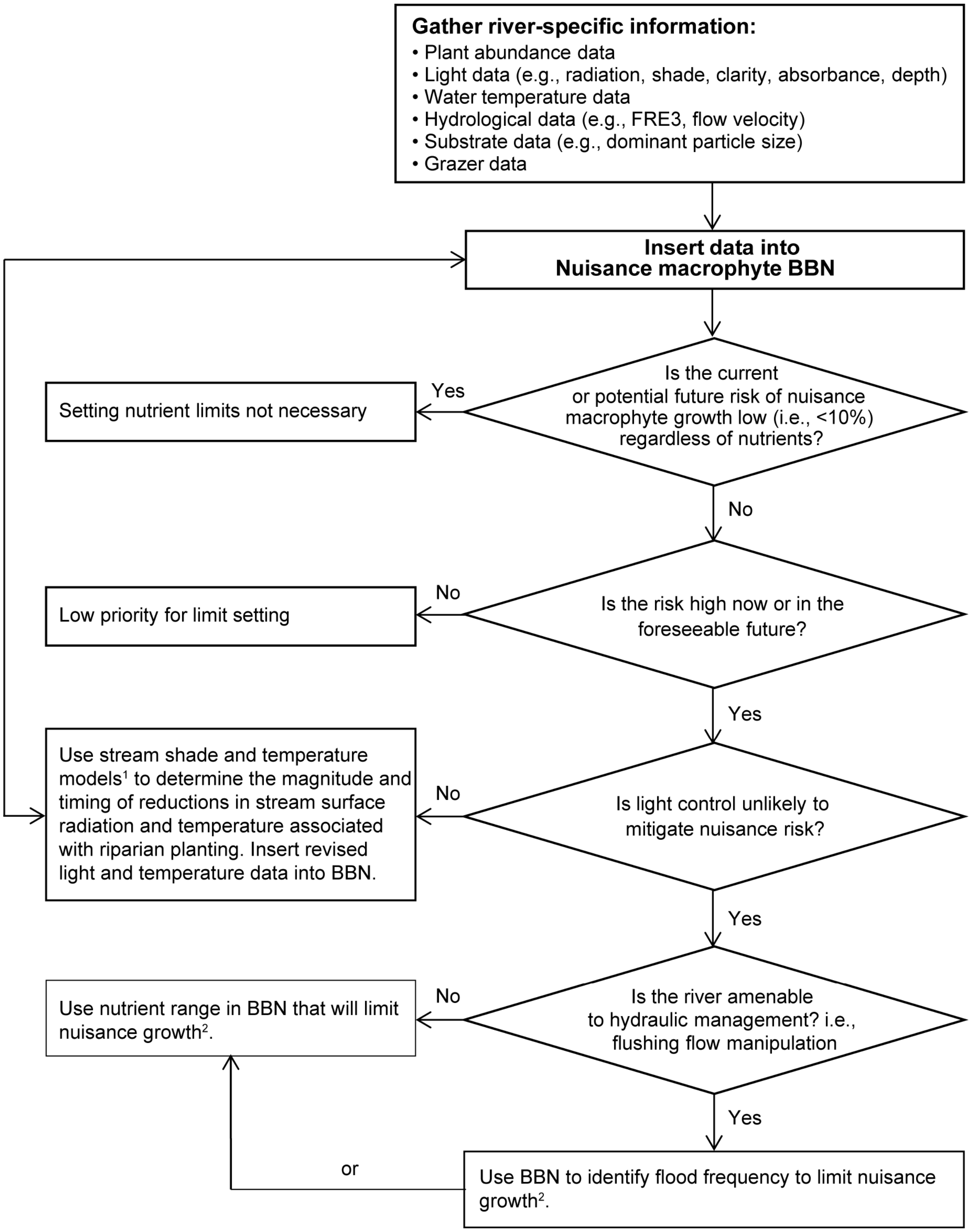

Figure 7-6: Decision-support framework to guide use of the nuisance macrophyte BBN and other existing tools for nutrient limit setting in relation to instream plant growth. [1] e.g., WAIORA, figures 6 and 7 Davies-Colley et al. (2009). [2] An alternative approach is to develop river-specific or river-type-specific mechanistic or empirical models e.g., Booker and Snelder 2012 (see Appendix I for further information).

8 Phytoplankton, cyanobacteria & didymo

Section summary:

- We have not developed instream phytoplankton standards or a model to predict the probability of nuisance phytoplankton growths in this study which has focused on plant growths in wadeable streams and rivers. Readers are referred to the approach taken in the Waikato River Independent Scoping Study as a guide to this process.
- The New Zealand interim cyanobacterial guidelines provide a simple decision tree to determine the potential for blooms of benthic cyanobacteria, which comprises a subset of the physico-chemical variables we have used to develop the BBNs in this study. We suggest that there is scope to produce a new BBN that predicts of the probability of cyanobacterial bloom alert levels if the periphyton cover protocols recommended for future data collection in this report are followed.
- The periphyton BBN that we have developed in this study does not apply to didymo-infested streams or rivers as this diatom does not appear to respond to some environmental variables in the same manner as other common New Zealand periphyton species.

8.1 Phytoplankton

We have not developed a model to predict the probability of nuisance phytoplankton growths developing in streams and rivers in this study. Nuisance phytoplankton blooms are generally only considered problematic in large, impounded river systems (e.g., Waikato hydrolakes and lower river) with relatively high nutrient levels and water residence times. As a consequence few Regional Councils systematically measure riverine phytoplankton abundance in streams and rivers as part of their State of Environment monitoring programmes. In this study we have focused on instream periphyton and macrophytes which are the dominant plant forms in wadeable streams and rivers.

In those instances where Regional Councils plan to set phytoplankton and nutrient standards for larger rivers the approach taken in the recent Waikato River Independent Scoping Study is probably useful as a guide to this process. Phytoplankton and nutrient concentration targets were devised for this river system (Table 8-1) based on a combination of ANZECC guidelines, Environment Waikato classifications and expert opinion of the study team (weight-of-evidence approach) (NIWA 2010). The study also took into account information indicating that the risk of phytoplankton community dominance by cyanobacterial species is low when total P concentrations are less than 35 mg m^{-3}, total N concentrations are less than 700 mg m^{-3} and when chl *a* levels are less than 10 mg m^{-3} (Downing et al. 2001).

Table 8-1: Targets for nutrients and chlorophyll a in the Waikato River system (NIWA 2010).

			Waikato River			Waipa River
			Upper	Middle	Lower	
Phosphorus	TP	mg m^{-3}	20	35	35	35
Nitrogen	TN	mg m^{-3}	300	500	500	500
Chl *a* - trigger	CHL	mg m^{-3}	5	5	5	5
Chl *a* - warning	CHL	mg m^{-3}	10	10	10	10
Chl *a* – filters	CHL	mg m^{-3}		20	20	20

8.2 Benthic cyanobacteria

In 2009, the Ministry for the Environment and Ministry of Health (MfE & MoH 2009) published a set of interim New Zealand guidelines for cyanobacteria in recreational freshwaters. The guidelines cover planktonic (i.e., free-floating, phytoplanktonic) and benthic (i.e., attached, periphytic) cyanobacteria. These interim guidelines provide alert level targets for "potentially toxic" benthic cyanobacterial abundance in locations used for contact recreation (Table 8-2).

The guidelines note that benthic, mat-forming cyanobacteria are widespread through New Zealand rivers and are found in a range of water quality conditions, including oligotrophic waters (Biggs and Kilroy 2000). The most common genus is considered to be *Phormidium*, which forms expansive, leathery, dark brown/black mats. The guidelines note that "there are many factors relating to human land uses and activities that cause cyanobacterial blooms and mats to form or that exacerbate naturally occurring blooms and mats (e.g., flow alteration, shade reduction, nutrient input)". They also state that "there are no national environmental indicators that relate to cyanobacterial bloom and mat events", although "some Regional Councils report qualitatively on cyanobacterial blooms and mats, and whether cyanotoxins were found".

Recent research on the Hutt and Wainuiomata Rivers (Heath et al. 2011) showed that percentage cover of *Phormidium* mats was greatest in the summer months and correlated to warmer water temperatures and stable river flows (mats were removed by floods in excess of three times the median flow). The presence/absence of mats was not correlated to concentrations of water soluble nutrients but, nevertheless, sites with the highest cyanobacterial coverage had high TN:TP ratios suggesting that nitrogen rather than phosphorus may be the nutrient limiting *Phormidium* mat growth. Toxin occurrence was restricted to periods of warm water temperates (>13.4°C) and below-average river flows.

Table 8-2: Summary and alert level framework for benthic cyanobacteria in the interim New Zealand guidelines for cyanobacteria in recreational freshwaters (MfE & MoH 2009).

Alert level [a]	Actions
Surveillance (green mode)	
Up to 20% coverage [b] of potentially toxigenic cyanobacteria attached to substrate.	• Undertake fortnightly surveys between spring and autumn at representative locations in the water body where known mat proliferations occur and where there is recreational use.
Alert (amber mode)	
20−50% coverage of potentially toxigenic cyanobacteria attached to substrate.	• Notify the public health unit. • Increase sampling to weekly. • Recommend erecting an information sign that provides the public with information on the appearance of mats and the potential risks. • Consider increasing the number of survey sites to enable risks to recreational users to be more accurately assessed. • If toxigenic cyanobacteria (see Table 2) dominate the samples, testing for cyanotoxins is advised. If cyanotoxins are detected in mats or water samples, consult the testing laboratory to determine if levels are hazardous.
Action (red mode)	
Situation 1: Greater than 50% coverage of potentially toxigenic cyanobacteria attached to substrate; or Situation 2: up to 50% where potentially toxigenic cyanobacteria are visibly detaching from the substrate, accumulating as scums along the river's edge or becoming exposed on the river's edge as the river level drops.	• Immediately notify the public health unit. • If potentially toxic taxa are present then consider testing samples for cyanotoxins. • Notify the public of the potential risk to health.

[a] The alert-level framework is based on an assessment of the percentage of river bed that a cyanobacterial mat covers at each site. However, local knowledge of other factors that indicate an increased risk of toxic cyanobacteria (e.g., human health effects, animal illnesses, prolonged low flows) should be taken into account when assessing a site status and may, in some cases, lead to an elevation of site status (eg, from surveillance to action), irrespective of mat coverage.

[b] This should be assessed by undertaking a site survey (more details provided in Section 4.4 of the Guidelines).

The New Zealand interim cyanobacterial guidelines provide a simple decision tree to determine the potential for blooms of benthic cyanobacteria (Figure 8-1). The components of the decision tree comprise a subset of those used in our nuisance filamentous periphyton BBN model and the thresholds defined in each are broadly compatible. We suggest therefore that there is scope in the future to produce and test a new BBN (e.g., using existing data and data gathered using periphyton cover protocols recommended in Appendix K of this report) that predicts of the probability of cyanobacterial bloom alert levels (i.e., green, amber, red) at sites.

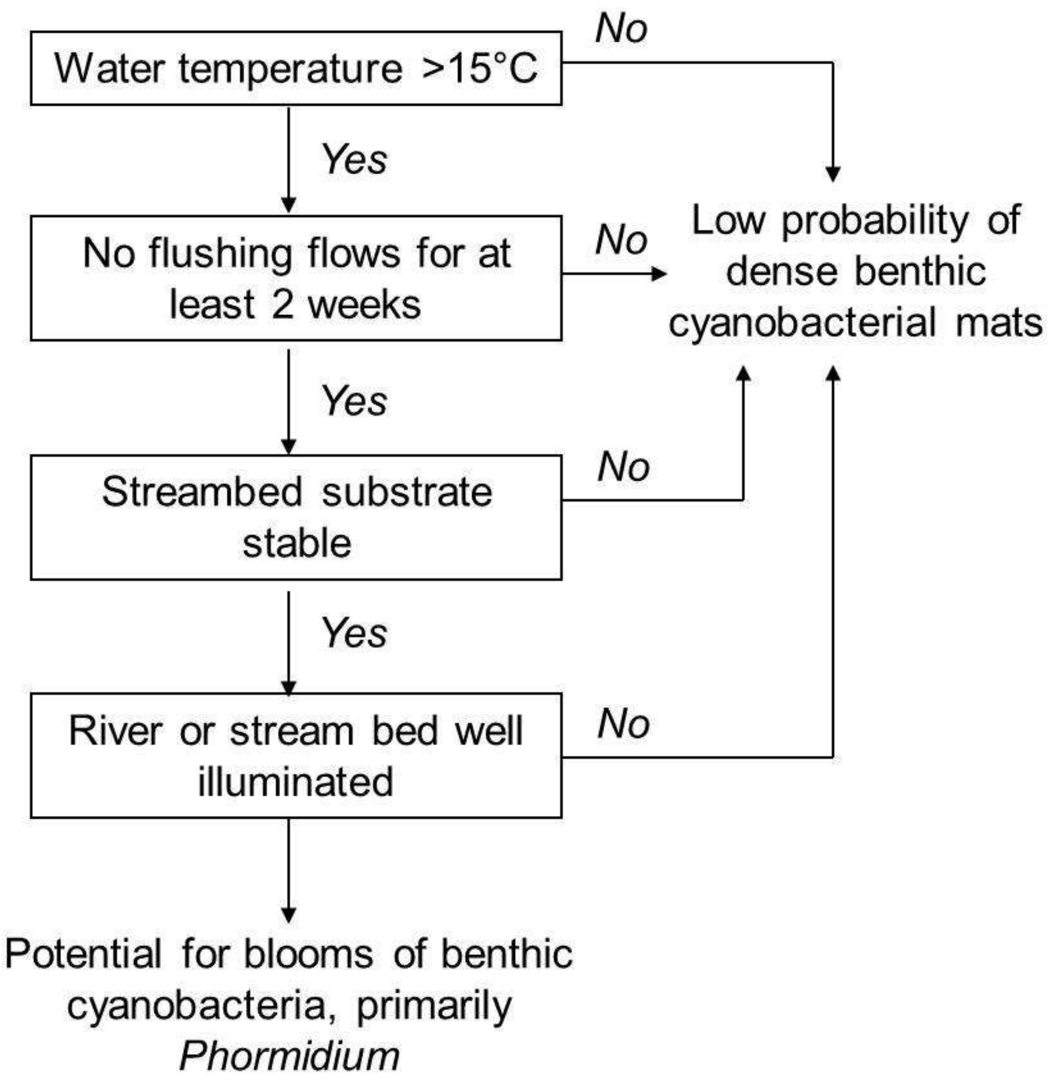

Figure 8-1: Decision tree to assess potential risk of benthic cyanobacterial bloom developing (MfE and MoH 2009).

8.3 Didymo

The BBNs we have developed do not apply to didymo-infested streams or rivers. The invasive freshwater diatom didymo is a special case, as it does not appear to respond to some environmental variables in the same manner as other common New Zealand periphyton species. Ecological studies (Kilroy et al. 2006) have shown that didymo biomass accumulation is higher with lower water temperatures (in contrast to most periphyton communities) and it is most prevalent in low nutrient systems (although within these systems it does appear to attain a higher biomass where nutrient concentrations are higher). It appears to prefer 'continental-type climate conditions' with large seasonal temperature differences (Kilroy et al. 2007). Didymo has a broad hydraulic range, thriving in very slow moving, shallow waters to beyond the range of river depths and velocities that can be safely sampled. Because of its robust growth habit, production of stalks that strongly attach to substrate, it appears to be able to grow almost anywhere in rivers where the substrate is not constantly unstable (Kilroy et al. 2006). Nevertheless, the results of predictive modeling, based on information from all sites that it has so far colonised in New Zealand South Island rivers, suggests a preference for stable, hard substrates and low flow variability, long time intervals between floods and sites with a high lake influence (Kilroy et al. 2007).

Didymo proliferations have been shown to affect benthic invertebrate communities and water quality (i.e., increase pH to >9 in weakly buffered waters dominated by snowmelt, which if sustained may be deleterious to fish), but so far no clear flow-on effects have been documented for native fish or trout (Larned et al. 2007). Benthic invertebrate abundance and diversity have been shown to increase with proliferations of didymo; however they also cause a shift in community composition from a predominance of EPT taxa to a predominance of crustaceans, non-EPT insects, and worms. These trends are also evident for non-didymo periphyton communities in New Zealand. Some invertebrate grazers have been shown to consume didymo. In laboratory trials, mayfly (*Deleatidium* spp.) larvae, caddisfly (*Pycnocentrodes* spp.) larvae and the freshwater snail, *Potamopyrgus antipodarium*, consumed didymo; however, the conditions under which invertebrate grazing may substantially reduce didymo in rivers are unknown (Larned et al. 2007).

9 Future work

9.1 Related Core- and MBIE- funded research

9.1.1 Sustainable Water Allocation Programme

Within NIWA's core-funded *Sustainable Water Allocation Programme* research is being conducted to develop periphyton – flow – environment (including nutrients) relationships. The research falls under three inter-linked objectives in this programme. The broad aim of the programme is to demonstrate and quantify links between water resource use and environmental consequences.

1. *Develop relationships between river flows and plants (algae and macrophytes) to improve our ability to predict the effects of water allocation on river ecosystems and nutrients.*

Research to date includes trialling methods to define periphyton biomass This has involved examining relationships between visual estimates of periphyton cover and biomass (chl *a*) to quantify the uncertainty associated with both types of measurement; This should help with provision of guidelines applicable to both types of abundance measure in the future and to provide recommendations on their relative suitability for State of Environment monitoring purposes. This work will shortly be submitted for publication. The abstract is provided in Appendix J. This research has shown that visual assessments and derived chlorophyll *a* equivalents can distinguish sites and sampling occasions as effectively as observed chlorophyll *a* as well as providing useful information about the type of periphyton present. Other research planned or underway includes surveys to improve understanding of the effect of flows on macrophytes and vice versa and the role of stream geomorphology in Canterbury, refinement of periphyton – flow – environment relationships using regional datasets; preliminary investigations into the influence of periphyton community composition on flow- biomass relationships; and developing methods for adapting/enhancing existing habitat assessment tools (e.g., Instream Flow Incremental Methodology, IFIM) for application in low-elevation, low-gradient streams.

2. *Identify flow-biota relationships and variation explained by flow regime for periphyton and invertebrates and further develop a two-dimensional physically-based ecosystem model to incorporate removal of periphyton by flushing flows.*

To date work under this objective has included large-scale empirical flow-regime – biota modelling, mainly using the NRWQN data but also using the Horizons Regional Council periphyton dataset. Continuing work will focus on (a) modelling periphyton through time given sets of antecedent flow conditions; and (b) modelling the likely distribution of periphyton at a site over all time. Preliminary investigations into linking hydrology and hydraulics are planned.

3. *Continue development of the Environmental Flows Strategic Allocation Platform (EFSAP), a tool to assist large-scale water management decision making.*

EFSAP allows assessment the consequences of water management (e.g., abstractions, minimum flows) on both instream-values (defined by physical habitat) and out-of-stream use (security of supply). The tool currently relies on generalised habitat models to predict environmental consequences, and the research is currently focused on improving the uncertainties in those models (which links to other objectives in the programme).

9.1.2 Management of Cumulative Effects of Stressors on Aquatic Ecosystems Programme

NIWA is investigating factors controlling instream attenuation of nutrients as part of the MBIE funded research programme on *Management of Cumulative Effects of Stressors on Aquatic Ecosystems* (CO1X1005). To date this research has focused on the Tukituki River and included development of a mechanistic model, calibrated with information from the research surveys and monitoring data, linking periphyton accrual and nutrient attenuation over a 90 km reach between inputs of enriched groundwater and sewage discharges and the sea (Rutherford 2011). This modelling approach has potential for use where detailed guidance is required for nutrient management, as outlined in the decision-support framework for periphyton (Figure 7-5). The research is also providing information on (i) effects of periphyton biomass and other environmental factors on benthic metabolism and dissolved oxygen, and (ii) the comparison of methods for assessing periphyton biomass, including periphyton thickness assessed from settled volume of samples as an inexpensive quantitative method.

9.2 Summary and recommendations for Phase 3

9.2.1 Summary

The aim of Phase 3 of this project is for critical data gaps to be filled and for the preliminary framework developed under Phases 1 and 2 to be further refined. At the end of Phase 3 the project's overall objective is intended to be fulfilled. That objective is: "*to develop a decision-making framework which will allow councils throughout New Zealand to define defendable dissolved macronutrient concentrations (phosphorus, P; nitrogen, N) and instream plant abundances as water quality standards for a broad range of river types and hydrological regimes"*

A preliminary framework has been developed under Phases 1 and 2 which consists of:

1. *Recommendations for some new general provisional periphyton and macrophyte abundance guidelines (see Table 9-1 below)*.

This has addressed to some extent the project's objective to determine "*instream plant abundances as water quality standards for a broad range of river types and hydrological regimes*". However there are a number of outstanding gaps in the updated guidelines table (Table 9-1) that should be filled in Phase 3 and further refinement of provisional guidelines is recommended.

2. *Two decision support trees, one for periphyton and one for macrophytes, that incorporate two newly developed general Bayesian Belief Network Models to scope the risk of nuisance plant growths at sites and potential limiting nutrient ranges, and guide users to other existing tools as appropriate.*

This has provided a basic preliminary decision support tool to address the project's objective to "*define defendable dissolved macronutrient concentrations as water quality standards [to prevent nuisance instream plant growths] for a broad range of river types and hydrological regimes*".

Table 9-1: Existing and new instream plant abundance guidelines to protect river values. Guidelines generated by this project shown in bold font.

Value	Indicator	Guideline to protect value
Benthic biodiversity/ stream health/ life supporting capacity	Macrophyte channel cross-sectional area/volume (CAV)	**max. ≤50% (provisional)** [ab]
	Periphyton biomass (chla/AFDM)	max. ≤50 mg m^{-2} mean monthly ≤15 mg m^{-2} diatoms or filaments [ac]
	Periphyton weighted composite cover	**max. <20% excellent, 20-39% good, 40-55% fair, >55% poor (provisional)** [ac]
	Periphyton filamentous cover	- [de]
	Periphyton mat cover	- [de]
Trout fishery/angling	Macrophyte CAV	**max. ≤50% (provisional)** [abf]
	Periphyton biomass (chla/AFDM)	max. ≤200 mg m^{-2} (diatoms), ≤120 mg m^{-2} (filaments) ≤35 g AFDM m^{-2} [ag]
	Periphyton weighted composite cover	- [dh]
	Periphyton filamentous cover	max. ≤30%
	Periphyton mat cover	- [dh]
Aesthetic	Macrophyte water surface area cover (SA)	**max. ≤50% (provisional)** [ij]
	Periphyton weighted composite cover	**max. Nov to Apr ≤30%** [ij]
	Periphyton filamentous cover	max. Nov to Apr ≤30%
	Periphyton mat cover	max. Nov to Apr ≤60%
	Periphyton biomass (chla/AFDM)	max. Nov to Apr), ≤120 mg m^{-2} (filaments), ≤35 g AFDM m^{-2} [ij]
Contact recreation	Macrophyte CAV and/or SA	**max. ≤50% (provisional)** [ij]
	Periphyton weighted composite cover	**≤30%**[ij]
	Periphyton filamentous cover	max. Nov to Apr ≤30%
	Periphyton mat cover	max. Nov to Apr ≤60%
	Periphyton biomass (chla/AFDM)	max. Nov to Apr ≤120 mg m^{-2} (filaments), ≤35 g AFDM m^{-2} [ijk]
	Cyanobacterial mat cover	<20% surveillance, 20-50% alert, >50% action [il]
Flow conveyance	Macrophyte CAV	**max. ≤50% (provisional)** [m]
Water supply	Periphyton cover (weighted composite, filamentous, mat)	- [il]
	Periphyton biomass	- [il]
	Cyanobacterial mat cover	- [il]

[a] requires further data collection to refine.
[b] macrophyte CAV linked to diurnal dissolved oxygen minima data.
[c] periphyton chl *a* or cover as appropriate linked to macroinvertebrate community metrics.
[d] gaps could be filled with further analysis of the NRWQN database.
[e] examining relationships between periphyton filamentous and mat cover and macroinvertebrate community metrics.
[f] would also be advisable to examine relationships between macrophyte CAV and trout or trout prey item abundance.
[g] or research, examining periphyton chl a linked with trout or trout prey item abundance.
[h] examining relationships between periphyton composite, filamentous and mat cover and macroinvertebrate trout prey items (i.e., mayflies, net-spinning caddisflies) or deriving from biomass recommendation using periphyton chl a-cover relationship.
[i] requires research to develop/refine.
[j] relating on-site measurements of macrophyte SA or periphyton cover/biomass as appropriate to human perceptions of what constitutes an instream aesthetic or contact recreation nuisance.
[k] could also be derived from cover recommendation using periphyton chl *a*-cover relationship.
[l] linking cyanobacterial mat cover to toxin production threatening human/stock health, or periphyton biomass/cover to water supply taste and odour indicators.
[m] linking macrophyte CAV measurements to flow conveyance problems and flood events.

9.2.2 Recommendations

In Phase 3 of the project the Regional Councils have suggested that the revised framework and guideline document could be structured around the following six steps:

Step 1. Determining instream plant objectives and limits.

This would involve:

- maintaining a focus on limits and objectives for water management values
- populating Table 9-1
- recommending preferred, secondary and surrogate plant indicators to represent each management value
- defining the intended purpose for each limit (e.g., plan or policy objectives, State of Environment monitoring, consent conditions)
- for limits to protect recreation values, defining whether they apply in summer only.

There are a number of gaps in Table 9-1 that could potentially be filled with further analysis of the existing NRWQN dataset and use of the periphyton chlorophyll a – cover relationships that have been developed under core- and MBIE-funded research programmes (see Table notes and Section 9.1). To fill other gaps further Regional Council data collection, analysis of these new data, or targeted research efforts will be required (see Table notes).

Step 2. Identifying key environmental factors regulating growth.

This would involve:

- using the existing decision support trees
- modifying or adding to this decision support system to link it to each of the following steps (3-6)
- identifying knowledge gaps and prioritise research needs
- identifying best environmental indicators to use for each growth scenario
- providing linkages to most appropriate measurement protocols for these indicators (i.e., methods, frequency of measurement)
- determining degree of light effects on plant growth
- adding further steps to the existing decision trees or link to an additional tree to assist in decision making around the degree of influence of light on growth
- providing recommendations to measure light at the streambed or to model light/flow relationships.

The above would refine, if necessary, the list of key environmental variables identified in this report. This list of variables and their recommended measurement protocols are outlined in Appendix K. Recommendations to measure light at the stream bed are provided in Section

7.2.1. The existing NRWQN database could be used to explore whether light attenuation (K_d) can be effectively modelled based on flows and clarity or turbidity.

Step 3. *Determining whether flow is a key factor for growth and risk of nuisance growth*.

This step links closely to research in the *Sustainable Water Allocation Programme*.

This step would involve:

- adding further steps to the existing decision trees or a link to an additional tree to assist in decision making around flow variability/accrual period
- developing various scenarios depending on the resolution of available data (i.e., good flow record at site, known flow statistics, poor or no flow record, requirement for modelled flow statistics)
- recommending preferred flow statistics
- providing guidance on reliability of statistics depending on available data and period of record
- where modelled statistics must be used providing guidance outlining required model inputs
- recommending preferred inputs (e.g., maximum vs. mean daily flows, appropriate filter periods)
- where possible linking to existing or on-going work.

Step 4. Determining nutrient status and risk of nuisance growth.

This would involve:

- adding further steps to the existing decision trees or a link to an additional tree to assist in decision making around nutrient state
- developing various scenarios depending on the resolution of available data (i.e., good nutrient record, known nutrient state, poor or no nutrient record, requirement for modelled nutrient state)
- recommending preferred nutrient indicators/statistics (e.g., annual mean nutrient concentration, monthly concentration, enrichment index)
- providing linkages to most appropriate measurement protocols for these indicators (i.e., methods, frequency of measurement)
- providing guidance on reliability of statistics depending on available data and period of record
- where modelled nutrient state must be used provide guidance outlining best fit model and any required model inputs
- provide information on the limitations of the recommended models (e.g., CLUES use of total N only)

- where possible linking to existing or on-going work.

Step 5. Determining risk of nuisance growth for rivers where key factors for growth are flow and nutrient status (i.e., cannot be mitigated by shade, flow regulation or any other means).

This links to the *Sustainable Water Allocation Programme* objectives.

- accept that flow (~60%) and then nutrients (~40%) are key factors for risk of nuisance growths
- utilise a risk matrix (below) using information gathered through steps 3 and 4, assign sites to the matrix

Nutrient status (e.g., N and P enrichment index)	High			
	Moderate			
	Low			
		Low	Moderate	HIgh
		Flow variability/flood frequency (e.g., statistics such as FRE3, mean days of accrual).		

Step 6. Determining nutrient limits linked to instream plant objectives/limits where flow and nutrient status are the key factors for nuisance growth.

- model nutrient limits for various instream plant objectives (step 1) depending on the risk scenario (use matrix)
- use Regional Council and NRWQN datasets from sites that are open and clear water (no light constraints) and (flow) unregulated assigned to the risk matrix depending on flow variability and nutrient status
- different risk scenarios may warrant different modelling methods
- provide information on the limitations of the recommended models and required inputs for models.

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11 Abbreviations

AFDW/AFDM	Ash free dry weight/ash free dry mass
ACA	Annual composite average
ACM	Annual composite maximum
AFA	Annual filamentous average
AFM	Annual filamentous maximum
AMA	Annual mat average
AMM	Annual mat maximum
ANOVA	Analysis of variance
ANZECC	Australian and New Zealand Environment and Conservation Council
BBN	Bayesian Belief Network
CAV	Cross-sectional area/volume
Chl *a*	Chlorophyll a
CLUES	Catchment Land Use for Environmental Sustainability model
CO_2	Carbon dioxide
DO	Dissolved oxygen
DIN	Dissolved inorganic nitrogen
DRP	Dissolved reactive phosphorus
ECan	Environment Canterbury
EPSAF	Environmental Flows Strategic Allocation Platform
EPT	Ephemeroptera, Plecoptera and Trichoptera
FRE3	Frequency of floods three times the median flow
$FRE3_{Inst}$	Frequency of floods three times the median flow calculated using instantaneous flow data
FRE7	Frequency of floods seven times the median flow
HCO_3^-	Bicarbonate
IFIM	Instream Flow Incremental Methodology
Kd	Light attenuation coefficient
MBIS	Ministry of Business, Innovation and Employment

MCI	Macroinvertebrate Community Index
MfE	Ministry for the Environment
MoH	Ministry of Health
N	Nitrogen
NEMaR	National Environmental Monitoring and Reporting
NH_4-N/NH_4	Ammoniacal nitrogen
NO_3-N/NO_3	Nitrate nitrogen
NRWQN	National Rivers Water Quality Network
P	Phosphorus
PAR	Photosynthetically available radiation
PeriWCC	Periphyton weighted composite cover
OVERSEER®	A model for on-farm management and decision support
Q_{10}	Rate of increase for every 10°C rise in temperature
QMCI	Quantitative MCI
REC	River Environment Classification
SA	Surface area
SI	Substrate index
SPASMO	Soil-Plant-Atmosphere System Model
SQMCI	Semi-quantitative MCI
TN	Total nitrogen
TDP	Total dissolved phosphorus
TP	Total phosphorus
USEPA	United States Environmental Protection Agency
WAIORA	Water Allocation Impacts on River Attributes model.

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Appendix A Request and guidance for data collection

Envirolink Tools Project: Extension of instream plant and nutrient guidelines

Guidance for field data collection

This project seeks to collate and analyse existing Regional Council datasets that link nutrient concentrations and flow characteristics to the measurements of the abundance of periphyton and macrophytes in streams and rivers.

The project aims to develop "A decision-making framework which will allow councils throughout the country to define defendable dissolved macronutrient concentrations (N, P) and instream plant abundances as water quality standards for a broad range of river types and hydrological regimes. The work will be based on a risk-assessment model calibrated using all data available nationally".

Should Regional Councils have the resources to undertake some sampling over the summer of 2009-10, and beyond, to aid in data provision for this project, we recommend the following methods:

Periphyton (for periphyton dominated streams)

Visual assessment of abundance. This is the minimum requirement. Recommended methods are: (1) Biggs and Kilroy (2000) RAM 1 or 2 methods, see http://www.niwa.co.nz/our-science/freshwater/tools/periphyton (pp. 40-45);

Quantitative assessment of biomass (chl *a*). This is optional but would be ***very*** useful for guideline development. Recommended methods are: Biggs and Kilroy (2000) Quantitative protocols (pp. 46-52). Measure biomass as (i) chlorophyll *a*, (ii) ash free dry mass, and (iii) dry mass per unit area sampled.

Macrophytes (for macrophyte dominated streams)

Visual assessment of abundance. This is the minimum requirement. Determine the percentage cover of submerged, emergent and floating macrophytes across five representative transects. Identify macrophytes (and assign cover) to species level if possible using an identification guide. One is provided in Collier et al. (2007). Calculate macrophyte total cover and channel clogginess as a minimum but also native cover if possible. See Collier et al. (2007). http://www.ew.govt.nz/Publications/Technical-Reports/Regional-Guidelines-for-Ecological-Assessments-of-Freshwater-Environments-Aquatic-Plant-Cover-in-Wadeable-Streams.

Nutrients

DIN and DRP analysis of water samples collected in an acid-cleaned bottle from the centre of the stream/river. This is the minimum requirement. (Ideally analysis detection limits should be 1 mg m^{-3}).

As above, plus TN and TP analysis. Detection limits should be 20 mg m^{-3} and 1 mg m^{-3}, respectively. This is optional but would be useful.

Flow characteristics

Preferably a flow-gauged site will be used so there is a record of discharge, flow velocity and flood frequency. If not, measure discharge at the time of sampling using the SHAP discharge protocol or, at the very least, measure flow velocity. Use one of the SHAP current velocity protocols: (1) a velocity meter to measure velocity at 0.4 of the water depth, (2) the "orange" technique, or (3) the "ruler" method. See
http://www.envirolink.govt.nz/documents/streamhabitatassessmentprotocols.pdf

Substrate size

Visually estimate the substrate % size composition in the area sampled using the SHAP P2C size classes based on B axis (stone widths), i.e., bedrock; boulder (> 256 mm); cobble (64-255 mm); gravel (2-63 mm) and sand/silt/mud (<2 mm).

Shade

Estimate in-stream shading using the SHAP P2 or P3 protocols. P2: little or no shading, 10-25% shading, 25-50% shading, 50-80% shading >80% shading; P3: densiometer measurement of canopy cover.

We recommend the measurements be carried out on a fortnightly or monthly basis for as long as possible. It would be useful to have data from as many different river types in a region as possible.

Appendix B Macrophyte monitoring fieldsheet and worked example

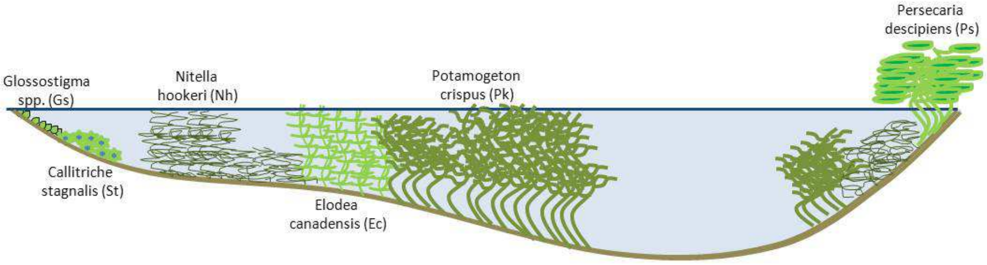
Macrophyte monitoring field sheet (adapted from Collier et al. 2007).

Stream/site: ____________________________________ Date: ________________________

Transcect	Wetted width (m)	Plant abundance (% of channel cross-sectional area/volume (CAV) or water surface area (SA) occupied)											
		Emergent			Submerged							Total	
		Species	% CAV	% SA	Surface-reaching			Below surface		Sub-total			
					Species	%CAV	%SA	Species	%CAV	%CAV	%SA	%CAV	%SA
1													
2													
3													
4													
5													

Emergent species:
An = *Apium nodiflorum* (water celery)
Gm = *Glyceria maxima* (reed sweetgrass)
Gr = other grass species (e.g., *Glyceria declinata/fluitans*)
Lp = *Ludwidgia palustris* (water purslane)
Mg = *Mimulus guttatus* (monkey musk)
Ma = *Myriophyllum aquaticum* (parrots feather)
Na = *Nasturtium officinale/microphyllum* (watercress)
Ph = *Persecaria hydropiper* (water pepper)
Ps = *Persecaria descipiens* (swamp willow weed)
Ve = *Veronica anagallis-aquatica/americana* (water speedwell)
Ml = *Myosotis laxa* (water forget-me-not)
NB. A pictorial guide for most common species is provided in Collier et al. (2007)

Submerged species:
Cd = *Ceratophyllum demersum* (hornwort)
Ec = *Elodea canadensis* (Canadian pondweed)
Ed = *Egeria densa*
Gs = *Glossostigma* spp.
Lm = *Lagaosiphon major*
Mp = *Myriophyllum propinquum*
Mt = *Myriophyllum triphyllum*
Nh = *Nitella hookeri/cristata*
Ns = *Nitella stuartii*
Pk = *Potamogeton crispus* (curled pondweed)
Po = *Potamogeton ochreatus* (blunt pondweed)
Rt = *Ranunculus tricophyllus* (water buttercup)
St = *Callitriche stagnalis* (starwort)



Transect	Wetted width (m)	Plant abundance (% of channel cross-sectional area/volume (CAV) or water surface area (SA) occupied)											
		Emergent			Submerged							Total	
		Species	% CAV	%SA	Surface-reaching			Below surface		Subtotal			
					Species	% CAV	%SA	Species	% CAV	% CAV	%SA	% CAV	%SA
1	12	Ps	5	10	Nh Ec Pk	10 10 15	10 10 15	Gs St Nh Pk	1 2 10 10	58	35	63	45
1 (without species ID)	12		5	10		35	35		23	58	35	63	45

Appendix C National Rivers Water Quality Network (NRWQN) data used in this study

Sites excluded from the analysis

AK1 and AK2 were excluded because these sites are located in deep rivers with silty beds that lack periphyton. RO2 and RO6 were excluded due to a large number of missing periphyton values. Sites RO1 and DN10 were excluded because they are lake outlet sites with unusually high periphyton cover. Northland sites WH2, WH3 and WH4 were deleted because periphyton cover is assessed along marginal macrophytes rather than the streambed at these unwadeable sites. Waikato river sites HM3-HM5 were excluded due to low wadeability and fluctuating river levels. Data from 1990-2006 inclusive were used, excluding years/sites affected by *Didymo* (Quinn and Raaphorst 2009). Summary statistics on the sites' attributes are provided in Table C-1.

Variables and methods

Periphyton cover by mats (> 2 mm thick) and filamentous growths is assessed monthly at NRWQN sites at 10 equidistant points across a standard, wadeable, cross-section at each network site where this is practicable.

Water quality variables are measured using monthly spot sampling (see Davies-Colley et al. (2011) for methods and metrics).

Site flow statistics were calculated from various sources. The $FRE3_{inst}$ was calculated for the period 1994-1999. Other flow variables were derived from the entire flow record available for each site (D. Booker, pers. comm.).

Light at the streambed was calculated from (1) annual average daily solar radiation from the NIWA National Climate Centre, (2) shade estimates by field teams (scaled from 1-5 relative to representative photographs), (3) average periphyton sampling depth estimated for each site by the NIWA field teams and (4) vertical light attenuation coefficient (k_d) calculated from black disc visibility (y_{bd}) and absorbance at 340 nm (g_{340}) (See Section 7.2.1.).

Benthic invertebrates are collected annually, under summer lowflow conditions, as 7 replicate Surber samples (0.1 m^2 area, 0.25 mm mesh net from wadeable run/riffle areas, samples composited for analysis) in which mean velocity and depth are measured and visual assessments are made of substrate particle size classes (modified Wentworth scale) and periphyton cover (%) as filamentous growths, mats (> 2 mm thick), and biofilms. These linked periphyton/benthic habitat data (1068 samples) were analysed to investigate influences of periphyton cover on macroinvertebrate metrics in Section 4.2.2.

Substrate composition was converted to a substrate index (SI) following Quinn and Hickey (1994), i.e., SI = 0.08x%boulder + 0.07x% large cobble + 0.06x%small cobble + 0.05x%large gravel + 0.04*%smallgravel + 0.03x% sand + 0.02x%silt.

Table C-1: Summary statistics for the 65 NRWQN sites used in BBN model development and evaluation.

Attribute	Mean	Median	StdDev	90%tile	10%tile
Average filamentous cover (%)	4.8	3.3	5.7	12.5	0.3
Average mat cover(%)	4.6	3.4	4.9	12.8	0.1
Average annual filamentous maximum cover (%)	18.7	14.4	17.0	47.5	1.9
Average annual mat maximum cover (%)	18.6	16.9	15.6	38.5	0.7
DRP (mg m^{-3})	7.8	5.3	8.7	18.0	1.2
TP (mg m^{-3})	47.2	31.6	42.7	112.6	12.4
DIN (mg m^{-3})	252.4	120.8	320.4	674.3	29.8
TN (mg m^{-3})	380.9	262.3	374.1	908.6	75.6
Average Temp (°C)	11.9	11.8	2.2	14.8	9.0
95% ile temp (°C)	18.4	18.2	2.8	21.7	14.7
Streambed light (µmol m^{-2} s^{-1})	960	950	144	1137	770
Black disc (m)	2.11	1.73	1.47	4.04	0.74
FRE_{inst}	21.5	19.8	15.1	40.5	0.8
Substrate Index	5.3	5.5	1.2	6.3	4.4
Macrograzers (n m^{-2})	1294	1052	1109	2357	232
Median flow (m^3 s^{-1})	72.7	29.1	121.2	261.9	3.6

Table C-2: Spearman rank correlations between invertebrate metrics and periphyton percentage cover measures using the National Rivers Water Quality Network 2000-2007 summer invertebrate sampling database. FA = Filamentous Algae, M = Mats (> 2 mm thick).

	MCI	QMCI	EPT richness	Total richness	% EPT	EPT density	Total abundance	FA	FA+M	FA+M/2
QMCI	0.57									
EPT richness	0.64	0.30								
Total richness	0.37	0.12	0.89							
% EPT	0.50	0.80	0.35	0.17						
EPTdensity	0.34	0.35	0.54	0.54	0.52					
Total abundance	0.03	-0.20	0.36	0.47	-0.10	0.73				
Filamentous Algae (FA)	-0.40	-0.47	-0.21	-0.09	-0.36	-0.08	0.18			
FA+Mat	-0.40	-0.51	-0.19	-0.07	-0.37	-0.08	0.18	0.80		
FA+Mat/2	-0.41	-0.52	-0.20	-0.08	-0.38	-0.08	0.19	0.86	0.99	
Mats	-0.15	-0.27	-0.02	0.03	-0.16	-0.03	0.09	0.21	0.65	0.56
Substrate Index	0.16	-0.07	0.15	0.09	0.08	0.02	-0.01	0.04	0.09	0.08
Velocity	0.04	-0.04	-0.03	-0.03	0.01	0.08	0.11	0.06	0.06	0.06
Depth	-0.19	-0.08	-0.14	-0.11	-0.07	-0.14	-0.13	0.06	0.04	0.04

Table C-3: Macroinvertebrate grazers of periphyton.

Acanthophlebia cruentata	*Olinga feredayi*
Acroperla trivacuata	*Oniscigaster distans*
Ameletopsis perscitus	*Oniscigaster wakefieldi*
Aoteapsyche catherinae	*Paracalliope fluviatillis*
Aoteapsyche colonica	*Paraleptamphopus caeruleus*
Aoteapsyche raruraru	*Paraleptamphopus subterraneus*
Aoteapsyche tepoka	*Paralimnophila skusei*
Aoteapsche tepua	*Phreatogammarus fragilis*
Aoteapsche spp.	*Physa acuta*
Aphrophila neozelandica	*Plectrocnemia maclachlani*
Atalophlebioides cromwelli	*Plectrocnemia spp.*
Austroclima jollyae	*Polycentropodidae*
Austroclima sepia	*Polyplectropus spp.*
Austroperla cyrene	*Potamopyrgus antipodarum*
Beraeoptera roria	*Pycnocentrella eruensis*
Blephariceridae	*Pycnocentria evecta*
Chiltonia spp.	*Pycnocentria funereal*
Confluens sp.	*Pycnocentria gunni (= C. gunni)*
Deleatidium spp.	*Pycnocentria sylvestris*
Ecnomidae	*Pycnocentrodes aeris*
Elmidae A	*Pycnocentrodes aureola*
Elmidae L	*Pycnocentrodes modesta*
Enochrus sp.	*Pycnocentrodes sp.*
Ephydrella sp.	*Rallidens mcfarlanei*
Eriopterini sp.	*Spaniocerca zelandica*
Ferrissia neozelanica	*Zelandobius confuses*
Gammaridae	*Zelandobius furcillatus*
Gyraulus corinna	*Zelandobius unicolor*
Gyraulus kahuica	*Zelandobius sp.*
Helicopsyche albescens	*Zelandoperla sp.*
Helicopsyche poutini	*Zelandoperla agnetis*
Helicopsyche zelandica	*Zelandoperla decorata*
Helicopsyche sp.	*Zelandoperla denticulata*
Hexatomini sp.	*Zelandoperla fenestrata*
Hudsonema aliena	*Zelolessica cheira*
Hudsonema amabilis	*Zephlebia borealis*
Ichthybotus hudsoni	*Zephlebia dentata*
Latia neritiodes	*Zephlebia inconspicua*
Lymnaea columella	*Zephlebia spectabilis*
Lymnaea tomentosa	*Zephlebia spp.*
Mauiulus luma	*Zephlebia versicolor*
Megaleptoperla diminuta	*Zephlebia borealis*
Megaleptoperla grandis	*Zephlebia dentata*
Neoscatella sp.	*Zephlebia inconspicua*
Neozephlebia scita	*Zephlebia spectabilis*
Nesameletus sp.	*Zephlebia spp.*
Nothodixa sp.	*Zephlebia versicolor*

Appendix D Flow statistics for Manawatu & Ruamahanga Rivers

Table D-1: Flow statistics for Manawatu and Ruamahanga Rivers.

FRE3 is the flood exceeding 3x the median flow (either on an annual or summer basis). Period between floods = 'filter period', interval period between flood peaks at which the 'flood' is assumed to be a single event (Hickey et al. 2004).

	Period between floods (days)	Number of floods	Floods/yr FRE3	Hours flood	Hours/year (h/y)	Hours/flood (h/f)	Days interflood (days of accrual)
Manawatu	1	284	16.5	18072	1048	63.6	22.2
(Ruahine str.)	2	274	15.9	17448	1012	63.7	23.0
17.24 yrs	3	258	15.0	16488	956	63.9	24.4
median [a]	4	246	14.3	15648	907	63.6	25.6
67 m^3/s	5	236	13.7	14880	863	63.1	26.7
Daily mean	6	224	13.0	13968	810	62.3	28.1
flow data	7	212	12.3	13128	761	61.9	29.7
			Floods/summer				
summer	1	145	8.4				21.8
median [a]	5	121	7				26.1
44.7 m^3/s							
Manawatu	1	476	27.6	17135	993	36.0	13.2
(Ruahine str.)	2	431	25.0	15654	907	36.3	14.6
17.24 years	3	401	23.2	14235	825	35.5	15.7
Median [a]	4	361	20.9	13175	763	36.5	17.5
67 m^3/s	5	342	19.8	12446	721	36.4	18.4
Instantaneous	6	328	19.0	11102	644	33.8	19.2
flow data	7	304	17.6	9862	571	32.4	20.7
summer	1	245	14.2				12.9
median [a]	5	178	10.3				17.8
44.7 m^3/s							
Ruamahanga	1	333	23.6	21216	1505	63.7	15.4
(Wardells)	2	322	22.8	20424	1449	63.4	16.0
14.1 yrs	3	301	21.4	19224	1364	63.8	17.1
median [a]	4	281	19.9	17904	1270	63.7	18.3
12.3 m^3/s	5	268	19.0	16680	1183	62.2	19.2
Daily mean	6	252	17.9	15744	1117	62.5	20.4
flow data	7	238	16.9	14808	1051	62.2	21.6
summer	1	188	13.3				13.8
median [a]	5	149	10.6				17.3
6.56 m^3/s							
Ruamahanga	1	616	43.7	19341	1372	31.4	8.4
14.1 yrs	2	533	37.8	17258	1224	32.4	9.7
median [a]	3	480	34.1	15370	1090	32.0	10.7
12.3 m^3/s	4	424	30.1	13982	992	33.0	12.1
Instantaneous	5	391	27.7	12611	895	32.2	13.1
flow data	6	367	26.0	11629	825	31.7	14.0
	7	339	24.0	10861	770	32.0	15.1
summer							
median [a]	1	331	23.5				7.8
6.56 m^3/s	5	207	14.7				12.4

[a] medians are based on instantaneous data from Tideda.

Appendix E Analysis of river types where existing nutrient guidelines apply

Evaluating the representativeness of the data used to develop nutrient – flow – periphyton relationships for New Zealand (Biggs 2000)

Cathy Kilroy
Ton Snelder
Doug Booker

Periphyton is an essential component of stream ecosystems because it is a major primary producer in flowing water. However, too much periphyton has detrimental effects on other components of the food web, on water quality, and on the aesthetic, recreational and economic values of streams and rivers. Major drivers of periphyton biomass in streams include nutrient concentrations and flow regime (Biggs and Close 1989; Biggs 1996). Both drivers are affected by human activities, especially land-use changes which change direct or diffuse nutrient inputs to streams, and which are accompanied by water abstraction or flow manipulation for irrigation and/or power generation. A challenge for managers is to predict the effects of such changes on periphyton biomass so that detrimental ecological effects can be avoided.

Currently the only nutrient – flow – periphyton relationships for New Zealand are a study that used data from 30 river sites throughout the country (Biggs 2000). Relatively strong relationships were found between maximum and mean periphyton biomass (measured as chlorophyll *a*), nutrient concentrations, and mean accrual time (defined as the mean time between floods with magnitude greater than 3 times the median flow).[1] These relationships have been applied for setting nutrient concentration and hydrological criteria and to predict the consequences of changes to flow regime and nutrient loads in streams and rivers throughout New Zealand (Biggs 2000). Following some anomalous results it has been suggested that one of the problems with the relationships is that they were derived from a particular type of river and therefore are not applicable to many other river types.

In this study we examined the Biggs (2000) dataset (hereafter referred to as the “2000 dataset”) to assess how representative the 30 sites were of all river segments in New Zealand. Identifying streams and rivers that were not represented in the 2000 dataset would indicate where the Biggs (2000) relationships are not applicable and suggest where further research is needed.

To make our assessment of the Biggs (2000) relationship nationally applicable we used modelled estimates of the three variables used in the relationship (dissolved inorganic nitrogen (DIN) [modelled as NO_3-N], dissolved reactive phosphorus (DRP), and time of accrual [modelled as FRE3]), which were available for all segments of the national river network. We substituted the modelled data at the sites in the 2000 dataset, rather than use the original measured data.

[11] In Biggs (2000) accrual time in days was calculated as 365/FRE3, where FRE3 = frequency of floods > 3 x median during the period of data collection. Whether instantaneous or daily average flow was used and a filter period between floods was not defined.

Modelled substrate was also included because of the importance of substrate in periphyton development. The 30 sites represented in the 2000 dataset all comprised gravel/cobble substrate.

Methods

We accessed modelled nitrogen (NO_3-N), phosphorus (DRP), FRE3 and substrate for each segment in the REC network of >570 000 segments. FRE3 was calculated from daily mean flow data using a 5 day filter period between floods (>3 times median flow). It is considered likely that an identical approach was used to derive FRE3 values in the Biggs (2000) dataset. These data were standardised to have mean of zero and standard deviation of one and were then partitioned into clusters of similar sites using the routine clara (Cluster package in R). We determined the membership of each of the 30 sites in the 2000 dataset in the generated clusters. We then calculated the total percentage of the clusters that had at least one of the 2000 dataset sites as a member, and compared proportions (%) belonging to each cluster for the whole network and for the 2000 dataset. This analysis was performed four times: with all the segments in the network (all_REC), and with the dataset excluding segments that represent small streams (i.e., stream order > 1) (REC_order>1); and for these two datasets partitioned 10 and 20 clusters. We used the REC_order>1 dataset because small streams (stream order = 1) make up about 50% of all segments, but were not represented in the 2000 dataset.

In addition we compared the proportions of stream segments assigned to the different categories of the first four levels of the REC (climate, topography, geology and landcover) in the 2000 dataset, and in the all_REC and REC_order>1 datasets. Finally we determined, for each dataset, the number of stream segments belonging to each category in the source-of-flow level of the REC (i.e., the combination of climate and topography). We included the REC dataset with stream order > 3 (REC_order>3) to assess representation of larger rivers by the 2000 dataset.

Results

For the all_REC dataset, seven of 10 clusters and 11 of 20 clusters were represented by at least one site in the 2000 dataset of 30 stream sites. Proportions of segments in the REC network not represented were 22% (10 clusters) and 36% (20 clusters) (Table E-1). Omitting all segments with stream order < 1 (REC_order>1) produced representation in eight of 10 clusters (9.4% of segments not represented) and 9 of 20 clusters (29% of segments not represented) (Table E-2).

In both REC network datasets (i.e., the all_REC and REC_order>1 datasets), the common clusters in the whole network also tended to be more common in the 2000 dataset, but there were exceptions. River network segments that were poorly or not represented by the 2000 dataset were those with fine substrate, and also those with medium-sized substrate and high nutrient levels. This result was consistent for all four analyses (Table E-1, Table E-2). A cluster of segments with coarse substrate, low-medium nutrients and high FRE3, and defined in the REC_order>1 dataset (20 cluster level) was also not represented in the 2000 dataset (Table E-2).

The representation of REC classes by the 2000 dataset is in proportion to the representation of the REC classes by the entire network. In other words, classes common/uncommon in the network were also common/uncommon in the 2000 dataset (Table E-3). The most marked differences in representation were in the WW (warm wet) class of climate and the L (lowland) class of source of flow, which were under-represented in the 2000 dataset. The CW (cool wet) climate class, H (hill-fed) class of source of flow, and IF (indigenous forest) class of land cover were all over-represented by 15% or more. No glacier-influenced or lake-fed segments were included in the 2000 dataset.

Based on the source-of-flow level of the REC, lowland rivers in general, and especially in the warm wet (WW) class, were largely unrepresented by the 2000 dataset (compare Figure E-1(a), (b) with Figure E-1(d)). Mountain-fed rivers (Topography, M) also had low representation. However, the 2000 dataset was a reasonable representation of larger rivers, as shown by a comparison of segments with stream order > 3 (compare Figure E-1(c) and (d)).

Table E-1: Summary of representation of clusters of New Zealand river segments (defined by cluster analysis of the entire network based on estimated substrate, NO_3_N, DRP and FRE3 characteristics) by the 30 sites comprising the 2000 dataset. For ease of interpretation, mean values of the four variables were classified into groups (high, medium, etc.,) defined as specified in the footnote table. Percentages of sites in each cluster are shown by shading from red (> 20%) to pale yellow (< 5%) to white (0%).

No. of clusters	Cluster characteristics				% cluster membership	
	Substrate	NO_3N	DRP	FRE3	all_REC	2000 dataset
10	vfine	vhigh	vhigh	medium	5.8	0.0
	fine	high	vhigh	medium	13.9	3.3
	fine	high	vhigh	high	11.9	0.0
	fine	vhigh	vhigh	low	4.4	0.0
	medium	low	medium	high	5.2	6.7
	medium	high	medium	medium	13.9	23.3
	medium	high	high	high	10	3.3
	coarse	low	medium	high	8.7	23.3
	coarse	low	medium	vhigh	12.6	20.0
	coarse	medium	medium	high	13.8	20.0
20	vfine	high	high	high	3.4	0.0
	vfine	vhigh	vhigh	medium	3.7	0.0
	fine	high	high	high	2.6	0.0
	fine	high	vhigh	low	4.7	0.0
	fine	vhigh	vhigh	low	3.8	0.0
	fine	vhigh	vhigh	high	6.2	0.0
	fine	xhigh	vhigh	low	2.6	0.0
	medium	medium	medium	medium	9.9	6.7
	medium	medium	medium	high	7.1	3.3
	medium	medium	medium	vhigh	2.6	10.0
	medium	high	vhigh	medium	5.3	3.3
	medium	vhigh	high	low	0.5	0.0
	medium	vhigh	vhigh	medium	0.4	0.0
	medium	vhigh	vhigh	vhigh	1.2	0.0
	coarse	low	low	high	10.8	26.7
	coarse	low	low	vhigh	5.3	6.7
	coarse	low	medium	vhigh	2.7	3.3
	coarse	low	medium	high	7.7	13.3
	coarse	medium	medium	medium	12.8	26.7
	coarse	high	high	high	6.6	0.0

Definitions of categories for cluster characteristics

		vfine	fine	medium	Coarse	
Substrate	index	<2.0 (silt/sand)	<3.0 (sand/gravel)	>3<4.4 (gravel/sm cobbles)	>4.4 (cobbles)	
		low	medium	high	vhigh	xhigh
NO_3N	g m^{-3}	<0.4	>0.4<0.75	>0.75<1.5	>1.5<3.0	> 3.0
DRP	g m^{-3}	<0.013	>0.013<0.025	>0.025<0.035	>0.035	
FRE3	floods yr^{-1}	<5.0	>5<7	>7<10	>10	

Table E-2: Summary of representation of clusters of New Zealand river segments (defined by cluster analysis of the network with stream order > 1 based on estimated substrate, NO_3_N, DRP and FRE3 characteristics, see footnote in Table 1) by the 30 sites comprising the 2000 dataset. Percentages of sites in each cluster are shown by shading from red (> 20%) to pale yellow (< 5%) %) to white (0%).

No. of clusters	Cluster characteristics				% cluster membership	
	Substrate	NO_3N	DRP	FRE3	REC_order>1	2000 dataset
10	fine	high	high	high	7.4	0.0
	fine	xhigh	high	low	2.0	0.0
	fine	vhigh	vhigh	medium	12.8	3.3
	medium	low	medium	high	12.5	23.3
	medium	medium	low	medium	13.4	23.3
	medium	medium	medium	medium	13.2	6.7
	medium	medium	medium	high	4.8	3.3
	medium	vhigh	high	low	3.6	3.3
	coarse	low	low	vhigh	14.3	16.7
	coarse	low	medium	high	15.9	20.0
20	vfine	high	vhigh	high	3.3	0.0
	vfine	vhigh	vhigh	low	2.5	0.0
	fine	high	high	low	6.0	3.3
	fine	high	high	high	6.2	0.0
	fine	vhigh	vhigh	high	3.9	0.0
	fine	xhigh	high	low	2.3	0.0
	medium	low	low	medium	4.5	6.7
	medium	low	medium	low	4.2	6.7
	medium	low	medium	high	8.6	6.7
	medium	medium	medium	medium	7.0	3.3
	medium	medium	medium	high	4.4	3.3
	medium	high	high	high	4.6	0.0
	medium	high	vhigh	low	1.5	0.0
	medium	vhigh	high	low	1.3	0.0
	coarse	low	low	medium	11.5	16.7
	coarse	low	low	high	2.1	3.3
	coarse	low	low	vhigh	8.4	13.3
	coarse	low	medium	high	7.5	20.0
	coarse	low	medium	vhigh	2.9	0.0
	coarse	medium	medium	medium	7.3	16.7

Table E-3: Percentage of river segments in categories of the first four levels of the REC for the whole network, the network excluding segments with stream order = 1, and in the 30 sites that comprise the 2000 dataset. Percentages of segments (network) or sites (2000 dataset) in each category are shown by shading from red (> 40%) to pale yellow (< 10%) to white (0%).

REC		Percentage in:		
level	class	all_REC	REC_order>1	2000 dataset
climate	CD	21.1	19.7	20.0
	CW	32.5	34.6	50.0
	CX	23.0	24.4	23.3
	WD	5.4	4.5	3.3
	WW	17.0	15.9	3.3
	WX	0.9	0.9	0.0
topography	GM	2.3	3.7	0.0
	H	34.1	34.7	60.0
	L	44.6	40.9	23.3
	Lk	2.3	3.2	0.0
	M	16.7	17.6	16.7
geology	Al	11.2	9.5	10.0
	HS	39.2	41.5	43.3
	M	5.0	4.0	0.0
	Pl	6.5	6.4	3.3
	SS	20.8	21.1	20.0
	VA	15.9	16.1	20.0
	VB	1.5	1.3	3.3
landcover	B	5.7	6.9	0.0
	EF	5.0	4.4	3.3
	IF	24.3	25.0	40.0
	M	0.6	0.1	0.0
	P	42.0	42.0	40.0
	S	5.4	4.2	3.3
	T	16.1	16.8	13.3
	U	0.7	0.6	0.0
	W	0.1	0.1	0.0

(a) all_REC

Topography	CD	CW	CX	WD	WW	WX
GM		145	15391			
M	5927	45155	46417			
Lk	2941	5116	4282	582	807	9
H	50196	89676	51944	1	1845	1129
L	62308	45995	17551	30515	94317	4024

Climate

(b) REC_order>1

Topography	CD	CW	CX	WD	WW	WX
GM		145	10997			
M	3132	24379	22207			
Lk	964	3786	3753	175	527	6
H	23759	45976	25748		962	650
L	27683	22614	6886	12345	43131	1922

Climate

(c) REC_order>3

Topography	CD	CW	CX	WD	WW	WX
GM		136	4576			
M	929	6479	4253			
Lk	623	3219	2700	36	287	
H	5945	13358	7087		163	201
L	5309	6021	967	1498	9044	503

Climate

(d) 2000 Dataset

Topography	CD	CW	CX	WD	WW	WX
GM						
M		4	1			
Lk						
H	5	10	3			
L	1	1	3	1	1	

Climate

Figure E-1: Numbers of segments in different classes of the Source of flow level in the REC, using four datasets: all_ REC, REC_order>1, REC_order>3, and the 2000 dataset. Shading highlights the proportion of segments in the different REC classes, decreasing from red to pale yellow. The figure highlights that the 2000 dataset best represents larger rivers in the whole network (REC_order>3), in cooler areas (climate CD, CW, CX).

Discussion

The data used by Biggs (2000) to develop nutrient – flow – periphyton relationships were derived from 30 sites described as follows:

"All sites were in streams and rivers flowing from hill-country watersheds where snowmelt affected flow regimes for ~3 mo/y, and lakes or large springs did not dominate flow regimes. None of the sites were affected by point-source pollution discharges or significant shading from riparian vegetation. The streams or rivers covered a broad range of enrichment regimes, reflecting differences in catchment land use and geology, and varied broadly in frequency of flood events, reflecting differences in local climate regimes" (Biggs 2000).

The present analysis using the REC classification and associated data confirms that the 2000 dataset conformed very well to this summary. The description justifies the over-representation of sites in the REC climate category CW (cool wet) and in the H (hill-fed) source of flow category. Representation of the different REC geology categories by the 2000 sites was remarkably similar to the proportion of segments assigned to the geology categories over the whole country, and was very close in the landcover categories given the low number of sites.

Restriction of the 2000 dataset to a specific river type was justified because previous analyses had already demonstrated that periphyton biomass and community characteristics, and the potential for nuisance blooms, in rivers across New Zealand vary with environmental conditions. For example, from nationwide surveys in the "100 Rivers" study of the 1980s, seven broad classes of periphyton were identified, based on their dominant taxa. These classes were found to be linked to hydrological and catchment variables as well as to water chemistry (Biggs 1990). Therefore it is reasonable to assume that the nutrient – flow – periphyton relationships developed for this specific river type will not apply to other river types. This was explicitly stated by Biggs (2000):

"The predictive ability of my dissolved nutrient-biomass models now needs to be tested, but several constraints should be considered. First, the models were derived for unshaded streams and therefore do not account for temporal or spatial variability in light. Second, the relationships were derived for streams with coarse gravel and cobble substrata. These models will generally overestimate benthic algal biomass in streams with extensive areas of sand and silt …. Third, the utility of a flow threshold of 3 X median discharge to define a disturbance and commencement of biomass accrual needs to be more widely assessed."

In the present study, the cluster analyses indicated that within the range of the specific variables used to develop nutrient – flow – periphyton relationships approximately 30% of all segments within New Zealand may not be represented by the 2000 dataset. Furthermore, regional differences in periphyton communities were identified in the 100 rivers study, in that some of the seven periphyton classes distinguished were largely confined to certain areas, and there were marked differences in biomass among the seven classes (Biggs 1990). Consequently, we may expect that relationships developed for specific regions will explain more variation than those developed for the entire country, albeit restricted to a certain river type. The implication is that more robust predictions of the responses of primary producers (periphyton) to changes in both nutrient inputs and flow regime may be provided by region-specific relationships that cover specific river types of interest.

This point was made in the 2000 analysis:

"The models presented here may provide a valuable tool to enable discharge and dissolved nutrient data to be used more extensively for making management decisions. Moreover, the data sets currently held by many government agencies may be useful in testing my models or constructing similar models that are more specific to an ecoregion. The result could be increased explanatory power and improved ability to manage stream eutrophication at the local scale." (Biggs 2000).

Given probable regional differentiation of periphyton responses, the obvious limitation of the 2000 dataset was its small size. While the 30 sites represented a good range of sites primarily within a defined river type, the sites were located throughout New Zealand, with low representation in different regions. Figure E-1 in particular highlights lack of representation in warm regions.

Conclusion

Our analysis confirms that the 2000 dataset of 30 river sites, used to develop nutrient – flow – periphyton relationships (Biggs 2000) was a good representation of hill-fed, cobble-bed rivers in New Zealand. Other river types, notably low-order lowland streams in warm areas, were not represented. Unrepresented river types are likely to account for about 30% of all river segments. The 2000 dataset did not account for likely regional differences in periphyton – environment relationships, and this was hampered by the small size of the dataset. The limitations of the nutrient – flow – periphyton relationships developed from the 2000 dataset were clearly stated by Biggs (2000). Thus, current efforts to accumulate more data on a regional basis are justified.

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Appendix F Summary of Regional Council data

Table F-1: List of environmental variables supplied by the Regional Councils.

Regional Council	Light at bed				Flow velocity		Flood frequency		Substrate type	Water temp	Macrophyte species	Macrograzer abundance		Nutrients			
	Black /Secchi disk	Abs (340&740)	Shade	Depth	Q [a]	Wetted width [a]	Ann FRE3 [b]	Ann FRE7 [b]			(nuisance colonist availability)	Invert	Other	DIN	DRP	Sed TN [c]	Sed TP [c]
ARC																	
EBOP																	
ECAN										Yes				Yes	Yes		
ES	Yes				Yes					Yes				Yes	Yes		
EW	Yes	Yes	Yes	Yes	Yes	Yes			Yes	Yes				Yes	Yes		
GWRC	Yes		Yes		Yes					Yes				Yes	Yes		
HRC							Yes		Yes					Yes	Yes		
HBRC			Yes		Yes				Yes	Yes				Yes	Yes		
MDC																	
NRC	Yes	Yes	Yes	Yes	Yes	Yes			Yes	Yes				Yes	Yes		
ORC			Yes	Yes	Yes	Yes			Yes	Yes				Yes	Yes		
TDC	Yes	Yes												Yes	Yes		
TRC	Yes				Yes				Yes	Yes				Yes	Yes		
WCRC	Yes				Yes					Yes				Yes	Yes		

[a] to estimate flow velocity if not measured directly, may not be available for all sites.

[b] if unavailable can be calculated/approximated from instantaneous/daily discharge records.

[c] variable not essential to run BBN model.

Table F-2 Periphyton and macrophyte abundance variables supplied by the Regional Councils.

Regional Council or NRWQN	Periphyton					Macrophyte		
	Mat cover (%)	Filamentous cover (%)	Total cover (%)	Chl *a* (mg m^{-2})	Score	Cover (%)	Volume (%)	Species ID
ARC								
EBOP								
ECAN	Yes	Yes	Yes		Yes	Yes		
ES				Yes	Yes			
EW		Yes	Yes			Yes		
GWRC	Yes	Yes	Yes	Yes				
HRC	Yes	Yes	Yes	Yes				
HBRC			Yes[1]	Yes		Yes[1]		
MDC								
NRC		Yes	Yes			Yes[1]		
ORC			Yes			Yes		
TDC		Yes			Yes			
TRC	Yes	Yes	Yes					
WCRC		Yes			Yes			

[1] A cover class estimate is made as opposed to recording an exact percentage.

Appendix G Periphyton BBN testing results for the National Rivers Water Quality Network database

Table G-1: Periphyton BBN testing results for the NRWQN data. Predictions were performed using the periphyton BBN. Prediction probability: <12.5% no nuisance, >12.5% likely nuisance. Sites that periodically experience actual nuisance filamentous growths (average annual maximums >30%) are shaded in grey. Predictions highlighted in bold do not match the model prediction >12.5% probability of nuisance cover. AFM = Annual; Maximum Filamentous cover; PeriWCC = Composite (Filamentous + Mat/2) Annual Maximum cover. Dominant substrate: LC = large cobble; SC = small cobble; LG = large gravel; SG = small gravel; Sa = sand; Si = silt.

Site	Temp 95% (°C)	Bed PAR (μmol m^{-2} s^{-1})	Substrate Index (dom)	DRP (mg m^{-3})	DIN (mg m^{-3})	TN (mg m^{-3})	FRE3 (n y^{-1})	Invert macro grazers (n m^{-2})	Prediction probability (%)	AFM	ACM	Comments on mis-predictions
AX1	17.0	635	6.6 (LC)	0.7	41	79	<1	93	<1	9	14	
AX2	16.3	602	5.1 (LG)	1.0	31	83	<1	195	<1	6	6	
AX3	15.4	493	5.6 (SC)	0.9	22	75	12	174	<1	2	5	
AX4	16.7	567	5.7 (SC)	0.9	44	96	<1	293	**<1**	44	67	Under, limiting nutrient levels but unusual flow below Roxburgh Dam with daily fluctuations, but low FRE3
CH1	14.9	482	6.3 (SC)	1.2	18	71	15	438	<1	9	24	
CH2	18.3	586	5.8 (SC)	3.5	287	369	13	1828	5	11	28	
CH3	14.4	453	5.7 (SC)	2.1	67	105	25	364	<1	5	13	
CH4	20.5	588	4.8 (LG)	2.1	79	123	24	255	3	4	13	
DN1	17.2	162	5.8 (SC)	16.8	36	313	6	1290	1	16	28	
DN2	16.5	439	6.3 (SC)	5.8	33	271	29	2961	<1	14	31	
DN3	18.8	396	5.4 (LG)	10.0	54	328	14	2911	**7**	50	59	Under, prediction 29.4% if TN (>300 ug/L) used instead of low DIN
DN4	17.6	412		2.2	93	175	<1		2	8	14	
DN5	17.1	361	4.8 (LG)	18.8	1020	1273	11	1496	29	32	47	
DN6	13.9	603	5.1 (LG)	6.3	233	301	20	2030	2	6	10	
DN7	16.3	518	5.4 (LG)	2.6	418	528	23	1662	6	2	6	
DN8	19.3	420	4.7 (LG)	7.0	900	1074	16	1421	**21**	26	38	Over, marginal
DN9	17.8	256	5.0 (LG)	2.6	176	302	15	293	1	12	20	
GS1	26.3	452	1.6 (Sa)	3.6	146	349	24		<1	14	31	
GS2	19.4	230	4.8 (LG)	7.8	207	385	28	2016	2	18	33	
GS3	19.7	468	5.0 (LG)	9.2	160	321	22	1672	15	31	49	
GS4	20.3	538	5.3 (LG)	11.4	70	138	24	100	7	25	44	
GY1	18.3	458	6.4 (SC)	2.2	54	154	33	137	<1	8	17	
GY2	19.1	474	6.7 (LC)	2.7	94	212	34	269	<1	20	30	

Site	Temp 95% (°C)	Bed PAR (μmol m^{-2} s^{-1})	Substrate Index (dom)	DRP (mg m^{-3})	DIN (mg m^{-3})	TN (mg m^{-3})	FRE3 (n y^{-1})	Invert macro grazers (n m^{-2})	Prediction probability (%)	AFM	ACM	Comments on mis-predictions
GY3	17.5	504	5.5 (SC-LG)	2.3	36	131	47	412	<1	13	22	
GY4	12.2	605	5.8 (SC)	1.2	37	74	40	221	<1	6	11	
HM1	18.2	339	5.4 (LG)	10.4	270	409	20	1749	4	3	7	
HM2	22.1	439	1.5 (Sa-Si)	22.8	759	1012	10		7	15	32	
HM6	22.0	354	5.7 (SC)	7.9	474	618	20	199	49	69	92	
HV1	17.7	541	5.4 (LG)	5.2	75	117	14	1328	3	4	5	
HV2	23.6	544	5.5 (SC-LG)	11.5	679	873	14	5032	33	61	66	
HV3	23.1	547	4.8 (LG)	7.5	97	183	16	2253	9	22	23	
HV4	18.1	456	6.7 (LC)	2.1	13	60	19	785	<1	2	3	
HV5	21.2	416	5.2 (LG)	8.9	107	207	9	520	12	10	10	
HV6	17.9	467	4.9 (LG)	6.1	162	234	12	1346	10	0	0	
NN1	19.0	430	5.9 (SC)	3.2	151	226	29	1817	1	14	40	
NN2	14.7	457	5.8 (SC)	2.5	26	60	35	1782	<1	0	5	
NN3	11.7	440	6.2 (SC)	3.1	16	50	19	979	<1	3	6	
NN4	21.3	527	5.7 (SC)	3.8	89	150	18	994	**4**	34	54	Under, low N&P
NN5	16.7	349	6.4 (SC)	1.4	32	102	16	741	<1	5	15	
RO3	17.4	353	4.3 (SG)	22.1	601	665	0	874	**42**	3	21	Over, large daily flow variation below Whaeo Dam
RO4	18.4	423	5.3 (LG)	20.6	124	214	6	1696	11	12	36	
RO5	19.9	567	3.8 (SG)	18.2	339	444	1	648	**21**	14	22	Over
TK1	17.1	497	5.6 (SC)	3.5	434	562	10	1599	11	26	36	
TK2	15.6	411	5.5 (SC-LG)	4.8	754	913	16	1329	2	17	29	
TK3	15.8	517	6.1 (SC)	2.6	267	398	20	910	1	26	45	
TK4	17.9	380	5.7 (SC)	1.0	16	67	1	97	<1	8	11	
TK5	18.5	451	5.3 (LG)	3.4	34	142	6	1653	**<1**	40	57	Under, low nuts, stable flow
TK6	17.4	258	6.1 (SC)	3.5	97	166	1	854	2	2	3	
TU1	19.5	779	5.8 (SC)	7.2	262	437	20	606	15	60	88	
TU2	13.8	779	5.7 (SC)	12.9	39	87	22	181	**<1**	56	74	Under, low N, managed flow
WA1	20.7	294	6.2 (SC)	6.4	318	563	40	118	**5**	32	40	Under. 49% if marginal T and light set to high class & FRE3 reduced to <25

Site	Temp 95% (°C)	Bed PAR (µmol m^{-2} s^{-1})	Substrate Index (dom)	DRP (mg m^{-3})	DIN (mg m^{-3})	TN (mg m^{-3})	FRE3 (n y^{-1})	Invert macro grazers (n m^{-2})	Prediction probability (%)	AFM	ACM	Comments on mis-predictions
WA2	15.2	248	5.7 (SC)	10.2	118	198	53	1432	<1	1	1	
WA3	20.6	364	6.0 (SC)	54.1	1900	2184	25	2812	**28**	14	16	Over
WA4	21.7	255	5.1 (LG)	5.4	211	448	20	461	8	7	8	
WA5	17.5	539	6.0 (SC)	5.1	106	254	28	1185	1	24	26	
WA6	20.0	425	5.6 (SC)	6.3	133	346	28	1150	2	25	25	
WA7	19.5	273	5.9 (SC)	11.6	517	812	19	5090	13	45	47	
WA8	21.1	337	4.9 (LG)	11.0	631	950	33	929	8	16	18	
WA9	21.7	322	4.4 (SG)	34.9	713	1065	33	313	14	49	51	
WH1	19.9	317	5.2 (LG)	4.9	30	122	31	3064	<1	13	13	
WN1	17.8	509	5.2 (LG)	7.5	264	366	46	319	2	28	54	
WN2	14.5	389	7.1 (LC)	3.8	40	112	60	1215	<1	0	1	
WN3	20.0	261	4.9 (LG)	14.7	484	652	41	2003	4	14	24	
WN4	20.1	281	5.4(LG)	12.2	615	782	50	1733	5	17	28	
WN5	17.5	539	5.9 (SC)	2.8	43	98	73	635	<1	2	3	

Appendix H BBN testing approach and results for Northland Regional Council data

This was the only dataset of those supplied by the Regional Councils that had data for most of the environmental and plant variables required to use the BBNs. However, missing from the Northland Regional Council (NRC) dataset was information on macrophyte and macroinvertebrate species, which were required to determine nuisance colonist availability in the macrophyte BBN and macrograzer abundance in both BBNs. Flow data were also unavailable for some sites which meant we were unable to estimate flow velocity, AnnFre3 and AnnFre7 for these sites. A further limitation of the NRC dataset was that macrophyte abundance was only recorded qualitatively (as none, rare, common or abundant). For the purposes of testing the macrophyte model we assumed that if macrophytes were recorded as 'abundant' this probably represented nuisance growth while other categories probably represented non-nuisance growth.

AnnFre3 and AnnFre7 were approximated from monthly discharge estimates for each site that had flow records. This is not at all ideal and we would normally recommend that these variables are calculated from instantaneous flow records if possible. Median discharge was determined for each site using as many complete years of data as were available. From these values we calculated the discharge corresponding to 3x and 7x the median flow for each site. The percentage of flow records for each site that were equal to, or exceeded, these values was then calculated. It was assumed that this percentage also represented the proportion of days in each year likely to experience a flow equal to, or in excess of, these values. The number of days in each year where flow was at or above 3x and 7x the median flow was calculated and this was assumed to represent the AnnFre3 and AnnFre7 values. Flow velocity ($m\ s^{-1}$) was estimated by dividing the mean discharge ($m^3\ s^{-1}$) by mean stream wetted vertical cross-sectional area (m^2). The latter was estimated from mean stream width (m) multiplied by mean stream depth (m) as recorded in the Council's semi-annual habitat surveys. Light at bed was calculated according to the protocol outlined in Section 7.2..1. We used NRC monthly water quality measurements of absorbance 340 and 740 and secchi/black disk readings to calculate an average K_d for each site. Average radiation for all sites was assumed to be the average across all Northland Region climate stations for 2010. We used the mean stream depth and channel shading values from the semi-annual habitat surveys. The dominant substrate at each site was determined from the habitat surveys as the substrate category (or categories) accounting for the highest percentage of stream bed area. Mean summer water temperature was determined as the average from monthly water quality records collected over the summer period (December to March inclusive) over all available complete summer periods for each site. Nutrient concentrations (DIN and DRP) were calculated as annual averages from monthly samples over all available complete years for each site.

We manually calculated overall prediction probabilities for each site ignoring those variables for which we had missing data (i.e., grazer abundance, colonist availability, flow velocity at some sites). For the macrophyte BBN it was assumed that an overall probability >50% indicated the likelihood of nuisance plant growth at a site, whilst a probability <50% indicated non-nuisance abundance. For the periphyton BBN we applied a more conservative 12.5% threshold consistent with the approach used for testing with the NRWQN dataset.

Table H-1: Macrophyte BBN testing results for Northland Regional Council data. Prediction probability: <50% no nuisance, >50% likely nuisance. Sites that periodically experience actual nuisance growths are shaded in grey. Mispredictions highlighted in bold.

Site		Light at bed (µmol m^{-2} s^{-1})	Velocity (m s^{-1})	AnnFre7 (n y^{-1})	Dom. substr.	Col. avail.	Grazers	Water temp (deg. C)	DIN (mg m^{-3})	DRP (mg m^{-3})	Nutrient status	PREDICTION (% prob.)	Actual abundance
Waiharakeke	**Value**	54	0.58	11	sand/silt	-	-	19.5	176	18	Adequate	4	Rare
(Stringers Rd)	**Prob.**	0.50	0.30	0.30	0.95			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Hatea	**Value**	68	0.04	0	boulder	-	-	20.5	427	13	Adequate	2	Rare
(Mair Rd)	**Prob.**	0.50	0.70	0.95	0.05			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Mangaharuru	**Value**	52	0.26	0	gravel	-	-	18.0	109	8	Limiting	9	Rare
(Main Rd)	**Prob.**	0.50	0.95	0.95	0.50			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Mangaharuru	**Value**	333	0.19	0	gravel	-	-	19.5	444	43	Adequate	**30**	**Abundant**
(Opotu Rd)	**Prob.**	0.95	0.70	0.95	0.50			0.90	n/a	n/a	0.70	**No nuisance**	**Nuisance**
Awanui	**Value**	334	0.66	0	boulder	-	-	19.8	68	19	Limiting	1	Common
(FNDC take)	**Prob.**	0.95	0.30	0.95	0.05			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Awanui	**Value**	64	0.27	0	hard clay	-	-	20.1	168	64	Adequate	41	Common
(Waihue)	**Prob.**	0.50	0.95	0.95	0.95			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Waipapa	**Value**	193	-	-	bedrock	-	-	19.4	335	5	Limiting	2	Common
(Landing)	**Prob.**	0.95			0.05			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Kerikeri	**Value**	256	-	-	boulder	-	-	22.0	447	11	Adequate	4	Rare
(Stone store)	**Prob.**	0.95			0.05			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Mangere	**Value**	95	0.13	1	hard clay	-	-	18.6	740	116	Adequate	30	Common
(Knight Rd)	**Prob.**	0.50	0.70	0.93	0.95			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Waiotu	**Value**	189	0.33	0	sand/silt	-	-	19.1	377	33	Adequate	78	Abundant
(SH1)	**Prob.**	0.95	0.95	0.95	0.95			0.90	n/a	n/a	0.70	Nuisance	Nuisance
Whakapara	**Value**	196	0.44	0	gravel	-	-	19.3	319	37	Adequate	41	Abundant
(Cableway)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.70	Nuisance	Nuisance
Kaihu	**Value**	397	0.68	0	boulder	-	-	18.1	294	14	Adequate	1	Rare
(Gorge)	**Prob.**	0.95	0.30	0.95	0.05			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Manganui	**Value**	103	0.62	2	sand/silt	-	-	21.1	242	110	Adequate	**13**	**Abundant**
(Perm/Mitaitai)	**Prob.**	0.50	0.30	0.95	0.95			0.90	n/a	n/a	0.70	**No nuisance**	**Nuisance**
Opouteke	**Value**	486	0.26	0	boulder	-	-	20.4	94	36	Limiting	2	Rare
(Suspension)	**Prob.**	0.95	0.95	0.95	0.05			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Kaeo	**Value**	316	0.43	3	gravel	-	-	19.1	78	9	Limiting	18	Rare
(Fire Station)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.30	No nuisance	No nuisance

Site		Light at bed (µmol m^{-2} s^{-1})	Velocity (m s^{-1})	AnnFre7 (n y^{-1})	Dom. substr.	Col. avail.	Grazers	Water temp (deg. C)	DIN (mg m^{-3})	DRP (mg m^{-3})	Nutrient status	PREDICTION (% prob.)	Actual abundance
Waitangi	**Value**	408	0.40	0	gravel	-	-	18.1	395	12	Adequate	41	Rare
(Waimate)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Waipoua	**Value**	262	0.40	0	boulder	-	-	16.5	37	16	Limiting	2	Rare
(SH12)	**Prob.**	0.95	0.95	0.95	0.05			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Ruakaka	**Value**	88	0.08	0	hard clay	-	-	16.5	504	92	Adequate	29	Rare
(Flyger Rd)	**Prob.**	0.50	0.70	0.95	0.90			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Punakitere	**Value**	191	0.45	1	gravel	-	-	18.9	466	31	Adequate	41	Rare
(Recorder)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Victoria	**Value**	383	0.27	0	cobble	-	-	17.7	35	19	Limiting	18	Common
(Thompsons)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Waiarohia	**Value**	325	0.20	0	cobble	-	-	19.1	386	12	Adequate	**41**	**Abundant**
(Whau Valley)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.70	**No nuisance**	**Nuisance**
Waiarohia	**Value**	327	0.20	0	gravel	-	-	22.2	409	17	Adequate	41	Common
(Second Ave)	**Prob.**	0.95	0.95	0.95	0.50			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Waipao	**Value**	405	0.20	0	grav/sand[a]	-	-	17.1	2617	31	Adequate	59	Abundant
(Draffin Rd)	**Prob.**	0.95	0.95	0.95	0.73			0.90	n/a	n/a	0.70	Nuisance	Nuisance
Paparoa	**Value**	232	-	-	grav/sand[a]	-	-	20.0	177	22	Adequate	**59**	**Rare**
(SH12 Bridge)	**Prob.**	0.95	-	-	0.73			0.90	n/a	n/a	0.70	**Nuisance**	**No nuisance**
Mangamuka	**Value**	661	-	-	gravel	-	-	17.6	25	29	Limiting	18	Rare
(Iwiatua Rd)	**Prob.**	0.95	-	-	0.50	-		0.90	n/a	n/a	0.30	No nuisance	No nuisance
Oruru	**Value**	491		0	grav/clay[a]	-	-	18.5	65	25	Limiting	**24**	**Abundant**
(Oruru Rd)	**Prob.**	0.95		0.95	0.73			0.90	n/a	n/a	0.30	**No nuisance**	**Nuisance**
Utakura	**Value**	61	-	-	sand/silt	-	-	19.9	185	24	Adequate	41	Common
(Rangihua)	**Prob.**	0.50	-	-	0.95			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Hakaru	**Value**	360	-	-	bed/bou	-	-	17.7	300	54	Adequate	4	Common
(SH1 Bridge)	**Prob.**	0.95	-	-	0.05			0.90	n/a	n/a	0.70	No nuisance	No nuisance
Mangakahia	**Value**	512	1.14	0	boulder	-	-	21.6	93	8	Limiting	0	Rare
(Twin Bridges)	**Prob.**	0.95	0.05	0.95	0.05			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Waimamaku	**Value**	370	-	-	bou/cob[a]	-	-	19.8	54	5	Limiting	10	Rare
(SH12)	**Prob.**	0.95	-	-	0.28			0.90	n/a	n/a	0.30	No nuisance	No nuisance
Ngunguru	**Value**	158	-	-	cobble	-	-	20.4	161	20	Adequate	41	Rare
(Waipoka Rd)	**Prob.**	0.95	-	-	0.50			0.90	n/a	n/a	0.70	No nuisance	No nuisance

Table H-2: Periphyton BBN testing results for Northland Regional Council data. Prediction calculations were performed manually rather than using the BBN due to data missing for some variables. Prediction probability: <12.5% no nuisance, >12.5% likely nuisance. Sites that periodically experience actual nuisance growths are shaded in grey. Mispredictions highlighted in bold.

Site		Light at bed (µmol m^{-2} s^{-1})	AnnFRE3 (n y^{-1})	Dominant substrate	Grazers	Water temp (deg. C)	DIN (mg m^{-3})	DRP (mg m^{-3})	PREDICTION (% prob.)	Filamentous cover (%)
Waiharakeke	**Value**	54	19	sand/silt	-	20.6	176	18	3	0
(Stringers Rd)	**Prob.**	0.65	0.70	0.1	-	0.6	0.5	1	No nuisance	No nuisance
Hatea	**Value**	68	9	boulder	-	22.8	427	13	**34**	**5**
(Mair Rd)	**Prob.**	0.65	0.70	1	-	1	1	0.7	**Nuisance**	**No nuisance**
Mangaharuru	**Value**	52	11	gravel	-	19.2	109	8	**14**	**10**
(Main Rd)	**Prob.**	0.65	0.70	0.7	-	0.6	0.25	0.7	**Nuisance**	**No nuisance**
Mangaharuru	**Value**	333	10	gravel	-	20.7	444	43	29	40
(Opotu Rd)	**Prob.**	0.95	0.70	0.7	-	0.6	1	1	Nuisance	Nuisance
Awanui	**Value**	334	10	boulder	-	21.4	68	19	49	70
(FNDC take)	**Prob.**	0.95	0.70	1	-	1	0.25	1	Nuisance	Nuisance
Awanui	**Value**	64	9	hard clay	-	22.1	168	64	5	30
(Waihue)	**Prob.**	0.65	0.3	0.05	-	1	0.5	1	No nuisance	No nuisance
Waipapa	**Value**	193	-	bedrock	-	22.8	335	5	34	35
(Landing)	**Prob.**	0.65	-	1	-	1	1	0.25	Nuisance	Nuisance
Kerikeri	**Value**	256	-	boulder	-	23.1	447	11	**48**	**10**
(Stone store)	**Prob.**	0.65	-	1	-	1	1	0.7	**Nuisance**	**No nuisance**
Mangere	**Value**	95	13	hard clay	-	20	740	116	3	30
(Knight Rd)	**Prob.**	0.65	0.70	0.1	-	0.6	1	1	No nuisance	No nuisance
Waiotu	**Value**	189	13	sand/silt	-	20.5	377	33	**3**	**40**
(SH1)	**Prob.**	0.65	0.70	0.1	-	0.6	1	1	**No nuisance**	**Nuisance**
Whakapara	**Value**	196	9	gravel	-	21.1	319	37	**34**	**20**
(Cableway)	**Prob.**	0.65	0.70	0.7	-	1	1	1	**Nuisance**	**No nuisance**
Kaihu	**Value**	397	8	boulder	-	19.7	294	14	**29**	**10**
(Gorge)	**Prob.**	0.95	0.70	1	-	0.6	0.5	0.7	**Nuisance**	**No nuisance**
Manganui	**Value**	103	20	sand/silt	-	22.9	242	110	5	9
(Perm/Mitaitai)	**Prob.**	0.65	0.70	0.1	-	1	0.5	1	No nuisance	No Nuisance
Opouteke	**Value**	486	6	boulder	-	23.5	94	36	49	95
(Suspension)	**Prob.**	0.95	0.70	1	-	0.7	0.25	1	Nuisance	Nuisance
Kaeo	**Value**	316	16	gravel	-	21.8	78	9	**34**	**10**
(Fire Station)	**Prob.**	0.95	0.70	0.7	-	1	0.25	0.7	**Nuisance**	**No nuisance**
Waitangi	**Value**	408	9	gravel	-	20	395	12	**21**	**5**
(Waimate)	**Prob.**	0.95	0.70	0.7	-	0.6	1	0.7	**Nuisance**	**No nuisance**
Waipoua	**Value**	262	10	boulder	-	17.9	37	16	10	5
(SH12)	**Prob.**	0.65	0.70	0.7	-	0.6	0.05	1	No nuisance	No nuisance

Site		Light at bed (µmol m^{-2} s^{-1})	AnnFRE3 (n y^{-1})	Dominant substrate	Grazers	Water temp (deg. C)	DIN (mg m^{-3})	DRP (mg m^{-3})	PREDICTION (% prob.)	Filamentous cover (%)
Ruakaka	**Value**	88	5	hard clay	-	18.6	504	92	3	10
(Flyger Rd)	**Prob.**	0.65	0.70	0.1	-	0.6	1	1	No nuisance	No nuisance
Punakitere	**Value**	191	10	gravel	-	21.2	466	31	**34**	**15**
(Recorder)	**Prob.**	0.65	0.70	0.7	-	1	1	1	**Nuisance**	**No nuisance**
Victoria	**Value**	383	3	cobble	-	19	35	19	6	5
(Thompsons)	**Prob.**	0.95	0.70	1	-	0.6	0.05	1	No nuisance	No nuisance
Waiarohia	**Value**	325	9	cobble	-	21	386	12	49	40
(Whau Valley)	**Prob.**	0.95	0.70	1	-	1	1	0.7	Nuisance	Nuisance
Waiarohia	**Value**	327	9	gravel	-	24.4	409	17	**49**	**2**
(Second Ave)	**Prob.**	0.95	0.70	0.7	-	1	1	1	**Nuisance**	**No nuisance**
Waipao	**Value**	405	4	gravel/sand/silt[a]	-	19.3	2617	31	5	0
(Draffin Rd)	**Prob.**	0.95	0.2	0.4	-	0.6	1	1	No nuisance	No nuisance
Paparoa	**Value**	232	-	gravel/sand/silt[a]	-	21.2	177	22	27	80
(SH12 Bridge)	**Prob.**	0.65	-	0.4	-	1	0.5	1	Nuisance	Nuisance
Mangamuka	**Value**	661	-	gravel	-	18.7	25	29	13	45
(Iwiatua Rd)	**Prob.**	0.95	-	0.7	-	0.6	0.05	1	Nuisance	Nuisance
Oruru	**Value**	491	6	gravel/hard clay[a]	-	21.3	65	25	**20**	**3**
(Oruru Rd)	**Prob.**	0.95	0.70	0.4	-	1	0.25	1	**Nuisance**	**No nuisance**
Utakura	**Value**	61	-	sand/silt	-	21.5	185	24	7	20
(Rangihua)	**Prob.**	0.65	-	0.1	-	1	0.5	1	No nuisance	No nuisance
Hakaru	**Value**	360	-	bedrock/boulder	-	20.4	300	54	60	80
(SH1 Bridge)	**Prob.**	0.95	-	1	-	0.6	1	1	Nuisance	Nuisance
Mangakahia	**Value**	512	10	boulder	-	22.4	93	8	**49**	**25**
(Twin Bridges)	**Prob.**	0.95	0.70	1	-	1	0.25	0.7	**Nuisance**	**No nuisance**
Waimamaku	**Value**	370	-	boulder/cobble[a]	-	22.7	54	5	**50**	**5**
(SH12)	**Prob.**	0.95	-	1	-	1	0.25	0.25	**Nuisance**	**No nuisance**
Ngunguru	**Value**	158	-	cobble	-	21.7	161	20	**68**	**3**
(Waipoka Rd)	**Prob.**	0.65	-	1	-	1	0.5	1	**Nuisance**	**No nuisance**

[a] dominant substrate spanned two model categories so we used an intermediate probability value in our manual calculations of the overall probability for these sites

Appendix I Summaries of river-type or river-specific mechanistic and empirical model development work

Note. These summaries emphasise the approach taken to model development and consequently differ from the report abstracts.

Tukituki River – Rutherford (2011)

NIWA leads a collaborative research project (which also involves Hawkes Bay Regional Council, Central Hawkes Bay District Council, Cawthron and GNS-Science) on nutrient dynamics and nuisance periphyton growth. During the summer of 2010-2011 experimental work was carried out in the Tukituki and Waipawa Rivers from upstream of the townships of Waipukurau and Waipawa to the mouth of the Tukituki at Haumoana. One of the outcomes from this work has been the development of a new, dynamic computer model which calculates nitrogen and phosphorus concentrations and periphyton biomass. This report details the development, calibration and testing of this nutrient-periphyton model.

The model developed comprises two sub-models: the hydraulic and the nutrient-biomass sub-models. The model is discretised by sub-dividing the river into segments of equal length (typically 1 km). Both sub-models operate on a sub-daily time step that depends on the velocity and the segment length. An explicit finite-difference scheme is used and, to ensure numerical stability, the time step is set to ensure that the Courant number (velocity x time step / segment length) is less than unity.

Hydraulic sub-model

The hydraulic sub-model estimates channel width (m), mean depth (m), mean velocity (m/s) and shear velocity (m/s) in each segment. Input data are:

1. Segment length (assumed uniform).
2. Daily mean inflow at:
    a. each tributary (including wastewater discharges), and
    b. the top boundary.
3. Equations relating each of depth, velocity and width to flow.

The hydraulics sub-model makes three simplifying assumptions.

First, inflows are assumed to vary linearly between the input daily values. Thus, at each time step the ‘new’ value of inflow at the top boundary and at tributary is calculated by linear interpolation of the mean daily flow time-series.

Second, flow is assumed to propagate along the channel instantaneously. Thus at each time step the ‘new’ flow in each segment is calculated by summing the ‘new’ inflows starting at the top boundary. In reality, any change in flow generates a ‘wave’ that takes a finite time to propagate downstream. However, the focus of the nutrient-biomass modelling is on summer low flows when changes in daily flow are small and the effects of this simplifying assumption are minor. The model needs to run during spates because these ‘reset’ biomass. However, during spates the focus is on modelling scour and it is not necessary to model the advection of nutrients and suspended biomass accurately.

Third, the river channel is assumed to be straight and uniform. Neither transverse nor longitudinal spatial variations in depth, velocity and width are currently incorporated in the model. The model therefore predicts segment average biomass and assumes that within-segment variations in depth and velocity do not have significant non-linear effects on periphyton-nutrient interactions.

Once segment flow has been calculated, mean depth, mean velocity and channel width are calculated for each segment from the rating equations provided as input data.

Nutrient sub-model

The nutrient-biomass sub-model simulates daily average photosynthesis, nutrient uptake and release. It does not simulate hourly changes that arise from diurnal variations in photosynthesis.

Periphyton biomass (BIO) is modelled as carbon (units: g C/m^2). Four forms of nitrogen in the water column are modelled: ammonium (AMM), nitrate and nitrite (NNN), dissolved organic nitrogen (DON) and particulate organic nitrogen (PN). The nitrogen content of biomass is calculated from biomass carbon (BIO) using a fixed C/N ratio. Three forms of phosphorus in the water column are modelled: dissolved reactive phosphorus (DRP), dissolved organic phosphorus (DOP) and particulate phosphorus (PP). The phosphorus content of biomass is calculated from biomass carbon (BIO) using a fixed C/P ratio. Suspended solids concentration (SS) is calculated from PN and/or PP using fixed C/P and C/N ratios.

The detailed equations are not listed here, but are provided in the report.

The model is coded in VBA in EXCEL. Equations are solved numerically using the 2-step Huan method. For low-moderate flows, at each half time step equations are solved in all segments, starting at the top boundary and moving downstream to the sea. Equations are solved first in the Waipawa River as far as its confluence with the Tukituki River. Equations are then solved along the Tukituki, with the Waipawa being treated as a tributary inflow. For other tributaries, time-series of flow and concentration are specified *a priori*. For high flows, nutrients are assumed to be conservative and periphyton biomass is reset to a prescribed low and uniform value. A series of simple test problems were simulated to confirm that the model conserves mass.

The model was calibrated by adjusting key coefficients by trial and error and making a visual assessment of the goodness of fit between observed and calculated longitudinal profiles of key parameters. Formal statistical goodness of fit measures (e.g., root mean square difference between observations and predictions) and automatic calibration methods were not employed because of the high spatial variability in the observations (e.g., periphyton biomass.

Model testing showed that the model successfully predicts the observed temporal patterns in DRP concentration and periphyton biomass – notably the high values during summer low flow and the consistently low values during winter high flow.

Predicted and observed biomass does not match quantitatively. There are three contributing factors. First, the model assumes the channel is uniform and that biomass occupies the entire bed area. Thus the model predicts ‘segment average’ biomass but there is high small-scale spatial variability in biomass which makes measuring ‘segment average’ biomass very difficult. Second, biomass is currently measured by collecting a small number of stones (typically 10). Although stones should be selected from random locations, in practice none are collected from deep water or where the current is very swift. This has the potential to bias measured biomass to shallow, tranquil parts of the river which are likely to have higher than average biomass. Third, although stones should be sampled across a range of size classes, in practice mostly cobbles are collected and gravel is seldom sampled although it occupies a significant proportion of the bed at some sites. Biomass tends to be higher on cobbles than gravels because they are subject to less abrasion by ‘rolling’ and the tops of cobbles are subject to less grazing by invertebrates which avoid exposure to predators like trout.

Consequently, it is considered unproductive to attempt to match observed periphyton biomass quantitatively (e.g., using automatic model calibration techniques). It may, however, be worthwhile to assess quantitatively the match between observed and predicted nutrient concentrations and possibly make slight adjustments to some model coefficients as a result. However, there is also uncertainty in the available concentration data, notably at the upstream model boundary and in the inflows which may hinder refinements to model calibration.

Currently the model assumes a uniform channel. The model does allow each segment to have separate depth-flow, velocity-flow and width-flow rating curves although this facility was not used during calibration and testing. Thus, in the future it would be possible to simulate runs, riffles and pools provided data were available from which to: (a) specify the proportions of the channel that are runs, pools and riffles, and (b) to develop rating curves representative of each type of channel. While this approach could account for longitudinal variations in channel hydraulics, it does not address the issue of small scale and transverse variations. One approach might be to develop a fully two-dimensional model but this would be a major undertaking. Alternatively, the current model could be modified by specifying *a priori* the fraction of the bed area in each segment on which biomass accrual occurs. It may be possible to do this based on particle size analysis (viz., to assume that particles above a certain ‘critical size’ accrue biomass while those below the critical size accrue no biomass). This would require additional fieldwork to measure particle size distributions and determine the ‘critical size’.

Overall the model is considered to be sufficiently well calibrated and tested to be used to investigate the effects of reducing phosphorus inputs (viz., land disposal of WWTP effluent) and increasing nitrogen inputs (viz., land use intensification on the Ruataniwha Plains). While there may be some uncertainty about the absolute values of predicted periphyton biomass and nutrient concentration, the model is expected to give a satisfactory and robust prediction about the changes in biomass and concentration likely to result from these management interventions.

Waiau River – Snelder et al. (2011)

Environment Canterbury (ECan) requested NIWA to assess the potential ecological effects of changes to mid-range flows in the Waiau River, North Canterbury. ECan provided a range of water management scenarios that will change the hydrological regime of the Waiau River. In particular, there will be changes to mid-range flows including altering the variability of flows, and alteration to the frequency and duration of high and low flows. The effects of these changes include reducing and removing periphyton (i.e., algae growing on the river bed).

The approach taken by this study was to quantify the change to hydrological indices (e.g., frequency of high flows) and physical variables, (e.g., river bed shear stress, sediment bedload transport capacity) that are associated with mid-range flows. The indices and variables were calculated and compared for the natural flow regime and for the flow regimes resulting from each of the six management scenarios. This physical information was then combined with ecological data to provide assessments of the likely effects of each scenario on the quantity of periphyton on the river bed.

Several hydrological indices were quantified representing the flow regime of the Waiau River for the natural flow and for the flow regimes resulting from each of the management scenarios. This analysis indicated that the flow management scenarios would be associated with only a relatively small change in mean annual maximum flow but larger changes to the mean flow. In addition, other indices that represent mid-range flows, the frequency of flow events with a magnitude of twice the median flow (FRE2) and the time between events exceeding this magnitude (DB2Q50), decreased and increased respectively with increase in the total allocation.

A hydraulic model of the Waiau River near Mouse Point was used to evaluate the degree of bed movement, flushing and bedload transport associated with the management scenarios. For this analysis it was assumed, based on a literature review, that filamentous algae and mats would be flushed by flows about twice the pre-existing flow and diatoms would be flushed by flows about five times the pre-existing flow. The analysis indicated that 61% of the median flow river bed would be surface flushed (i.e., fine material and filamentous periphyton would be removed) at a flow of twice the median flow.

The effectiveness of flood events for removing periphyton was examined at two sites for which there is long term data and that are similar to the Waiau: the Hurunui at State Highway 1 and Waimakariri at Gorge. At the Hurunui site, floods of at least 2 times the median flow (2Q50) were required to guarantee that the periphyton cover was reduced to low levels for a period of at least 20 days. For the Waimakariri site floods of at least 1.5 times the median flow were sufficient to guarantee low periphyton cover. The flows that are effective for flushing the Hurunui and Waimakariri sites (i.e., 2Q50 and 1.5Q50 respectively) are similar to the results of the hydrodynamic model simulations of the Waiau, which suggested surface flushing of the majority of the major braids at the 2Q50.

The periphyton data for the Hurunui and Waimakariri sites were used to develop simple empirical models for estimating the probability of exceeding periphyton guidelines on any day based on flow history. The assumption was made that biomass on any particular occasion is a function of the time since an effective flood (i.e., periphyton cover reduced to ~ zero). This period between flows that flush the bed is referred to as the accrual period (Da). This assumption is a simplification that was necessary because insufficient scientific knowledge is available to model the effect of other variables involved in periphyton biomass dynamics (i.e., light, temperature, nutrients, grazing). In addition, in this study there was no information available that described how these other variables would be changed as a result of abstraction.

Periphyton cover and mean daily flow data from 1989 to 2010 from the two NRWQN sites were analysed to provide models of the relationship between periphyton cover and flow history that could then be applied to the Waiau River. Observed periphyton cover was calculated for each sampling occasion by first calculating the mean of the 10 observations of proportion of cover by mats and filaments made on each sampling occasion. The two means (i.e., mats and filaments) were added to define the total periphyton cover. For each periphyton sampling occasion, the accrual time (Da; the time in days since the site had experienced flows of various magnitudes) was obtained from the mean daily flow record. Flow magnitudes were chosen that were 1, 1.5, 2, 3, 4 and 5 times the median flow (Q_{50}) at each site.

The effectiveness of flood events for removing periphyton at the Hurunui at State Highway 1 and Waimakariri at Gorge sites was evaluated by plotting the mean cover on each occasion as a function of Da. Periphyton cover was evaluated in terms of the Natural Resources Regional Plan (NRRP) objective for trophic state for alpine (lower) rivers which is for a maximum cover of the bed by filamentous periphyton of 20%, but a threshold of maximum total cover (i.e., mats plus filaments) of the bed of 30% was also used. The minimum accrual period required before the two periphyton thresholds were exceeded was quantified by extracting from the plots the minimum time between any flood (Da) and subsequent exceedance of a periphyton threshold. These data were used to develop simple models for estimating the probability of exceeding periphyton guidelines on any day based on mean daily flow history.

The models were developed by first estimating the probabilities of exceeding periphyton guidelines given Da, where Da was the time since flood events of two nominated magnitudes. The nominated flood event magnitudes were 2 and 3 times the median flow for the model based on the Hurunui River data and 1.5 and 2 times the median flow for the Waimakariri River data. The use of this two threshold “bi-variate” approach to estimating the probabilities of exceeding periphyton guidelines was chosen because it was clear that a degree of flushing (and periphyton removal) occurs over the entire flow range and that selection of two reasonably effective flood flows can better cover the range of flood flow events that may explain the periphyton cover on each sampling occasion. However, this is still considered to be a simplification of what is in reality a continuous relationship between antecedent flows and cover.

The days of accrual (Da) calculated for flood events of both flood event thresholds were subdivided into intervals bounded by 0, 5, 10, 25, 50, 100, and 450 days. The proportion of samples that exceeded the periphyton guidelines for every combination of these Da intervals were counted. The resulting analysis was expressed as matrices in which each cell is the probability of exceeding the guideline depending on the flow history expressed as Da. The time-series of natural and simulated residual flows for the Waiau River was the combined with the estimated probabilities of exceeding the guideline as a function of Da. For each daily time step (each day) of each time-series, Da was evaluated for the two flood event magnitudes for each model site (i.e., 2 and 3 times the median flow for the Hurunui River and 1.5 and 2 times the median flow for the Waimakariri River). For each time step the probability of exceeding the periphyton guideline was obtained for each respective model. For each scenario, this produced four time series of probabilities that guidelines would be exceeded (i.e., the two guidelines at the two sites; Hurunui at State Highway 1 and Waimakariri at Gorge).

These models indicated that the probability of exceeding the guidelines for any given proportion of the time is lowest for the natural flow and increases as the total allocation allowed by the management scenarios increases. However, the analysis also indicated that the nuances in the manner in which abstraction occurs that are specified by gaps and flow sharing for the management scenarios will have a negligible effect on the development of problematic levels of periphyton.

Lowland and spring-fed Canterbury streams – Booker and Snelder (2011)

Nutrient concentrations are one factor that can affect growth of macrophytes. Environment Canterbury (ECan) needs to establish nutrient concentration criteria for lowland and spring-fed streams as part of the development of limits to be set in a new Natural Resources Regional Plan (NRRP). The existing NRRP sets an objective for total cover by macrophytes in lowland streams to be less than 50%. Environment Canterbury (ECan) requires nutrient concentration criteria to meet these objectives in lowland and spring-fed streams and also requires information of how these criteria may need to change if the macrophyte objective was altered.

In this report data on in-stream macrophyte cover collected at sites across Canterbury by ECan was used to derive a predictive empirical model of macrophyte cover.

There are several factors that could be used to explain variation in macrophyte cover. For example, macrophyte cover may be greater in locations that have more nutrients, finer sediments, less shading and lesser flood frequency. Nutrient concentrations, sediment size, degree of shading and flood frequency are therefore examples of explanatory variables that could explain variability in macrophyte cover between sites. Explanatory data which potentially could be used to predict macrophyte cover were collated. As a result of previous studies, values for each explanatory variable were available for all (500,000) locations that comprise a digital representation of the New Zealand river network as defined in the River Environment Classification (REC). These data were extracted for each site for which macrophyte cover observations were available; and b) all river reaches of interest for this study. The locations of interest for this study were those within the network that satisfied the following criteria:

- located within Canterbury
- REC topography class of lowland source of flow
- segment elevation < 150 m
- REC land-cover class is not urban, and
- REC climate class is Cool Dry.

Collectively these locations broadly correspond to those classified as Spring-fed Plains and low lying locations within the Hill-fed Lower class in the NRRP.

M (mean annual maximum macrophyte cover) was modelled as a function of a number of potential predictor variables (FRE3 count, FRE7 count, mean duration of events exceeding the 75th flow percentile, average within segment mean summer (January) air temperature, segment slope, estimated riparian shade as a proportion of channel width, substrate, DIN and DRP). Temperature, slope, shade and substrate variables were obtained from the FWENZ database. Hydrological indices that describe the flow regime at each site and all other locations of interest were derived using a regression modelling approach. Hydrological indices derived for gauged sites were fitted to catchment characteristics using regression models. The hydrological dataset was acquired from the New Zealand national hydrometric database supplemented with data supplied by some regional councils including ECan and consisted of time-series of daily mean flow measured at selected gauging stations distributed throughout the country. The FWENZ database was used to provide catchment characteristics to be used as predictors of the hydrological indices. Random Forest regression models were fitted to each of the hydrological indices to estimate each of the hydrological indices for all sites.

A model was developed based on the following principles:

- that the model should be parsimonious (model complexity should be balanced against explanatory power)
- the model should conform to understanding of the system:
  - M should increase with SIN
  - M should increase with DRP
  - M should decrease with substrate size
  - M should decrease with flood frequency.

The FRE3Count was chosen to represent flood frequency in order to restrict the number of variables within the model. Models were developed using data from: a) all sites at where macrophyte sampling had been carried out (n = 168); and b) only lowland sites where macrophyte sampling had been carried out (n = 98). The predictive ability of the models as derived from these two datasets was compared.

Several models of M derived using different formulations and different input data sets were compared. From these models the one “best” model when compared to our selection criteria (parsimony and conforming to understanding of the system) was selected. This model was developed using M from all sites where M had been observed. The model included terms for FRE3Count, DIN, DRP, substrate size and the interaction between SIN and substrate size. Overall the model was highly significant (F-statistic = 53.59 on 5 and 162 degrees of freedom, $p < 0.001$) and explained 61% of the observed variation in M. All terms were significant ($p < 0.1$) and only one term (FRE3Count) had a p-value greater than 0.03.

A jack-knife cross-validation procedure was used to test for the ability of the model to predict M at an unvisited site. This cross-validation procedure was applied by leaving out all data associated with each of the 98 lowland sites at which observed values of M were available and then estimating M for the left-out site using data from all remaining sites. The results from this procedure produced estimates of M for each site as if macrophytes had never been sampled at that site. Jack-knifing therefore provides an objective measure of how well the model performs when predicting for an unvisited site. For each location at which macrophytes were observed, we calculated whether M was above 50%. This is ECan's NRRP objective for total macrophyte cover in spring-fed plains streams. Whether jack-knife predicted M was above or below 50% was calculated. This allowed an assessment of the proportion of sites for which either meeting or failing the objective was correctly predicted.

The results showed that the model was correct 85% of the time when predicting whether the objective for macrophytes is met at unvisited lowland sites.

The model was then used to predict the effect of changing nutrient criteria on macrophyte cover across all rivers in lowland Canterbury. Several scenarios with different nutrient concentration limits were used to assess the number of locations that would not meet the objective for total cover by macrophytes. Results indicated that increased nutrient supply in terms of dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) would cause increases in total cover by macrophytes.

For the majority of the scenarios it was assumed that imposing nutrient concentration limits would result in nutrient concentrations in all rivers being at that limit. Given this assumption, the model predicted that:

- given present conditions only 27% of locations in lowland streams in Canterbury meet the macrophyte cover objective
- if nutrients were set as the ANZECC guidelines default trigger values for low-elevation streams 91% of locations would meet the objective
- under an Extreme Nutrients (DIN 5 g m^{-3}; DRP 0.1 g m^{-3}) scenario only 18% of locations would meet the objective.

These results indicated that in order to set nutrient limits a judgement is required as to what level of compliance (i.e., what proportion of locations meeting the macrophyte cover objective) is acceptable. Some consideration of whether the setting of limits will cause increases in nutrients in locations which are currently under the limit is also necessary.

Appendix J Periphyton chlorophyll a versus visual estimates

Variability in estimates of periphyton standing crop in streams: a comparison of chlorophyll *a* sampling and visual estimates of cover

Kilroy, Booker, Drummond, Wech, Snelder

Abstract

Improved understanding of linkages between flow characteristics, nutrient concentrations and primary production (such as periphyton) in rivers is highly topical in New Zealand because of increasing pressure on river water resources and land usage, both of which potentially affect river values through changes to periphyton standing crop and community composition. Developing refined relationships and maintaining standards requires measurements of these variables over time. The most common metric representing periphyton standing crop is chlorophyll *a*, which requires laboratory processing of quantitatively collected field samples. Therefore, there is increasing interest in using visual estimates of periphyton cover, which are rapid and require no sample analysis. However visual estimates are often regarded as subjective, semi-quantitative, and prone to high inter-operator variability. To provide guidance on the reliability of visual estimates of periphyton cover we investigated variability in periphyton standing crop as determined by visual estimates of cover and chlorophyll a sampling. Following training in the methodology, three observers surveyed three river sites on three occasions using both methods. The visual estimate method comprised distinguishing up to eight categories of periphyton cover based on colour, thickness and algal type. We also developed a method for reducing visual estimates to a chlorophyll *a* equivalent. The visual assessments and the derived chlorophyll *a* equivalent distinguished sites and occasion as effectively as observed chlorophyll a, but also provided potentially useful information about the type of periphyton growing at each site. The largest discrepancies in visual assessments among observers were for categories of low periphyton biomass, which had an insignificant effect on derivation of a chlorophyll a equivalent. We confirmed the current recommendation of 20 views as sufficient to obtain a realistic average periphyton composition at a site. Because our surveys were conducted in only three rivers in Canterbury, applicability of the visual category – chlorophyll conversion factors to other rivers and regions is currently unknown. However, our results indicate that inter-operator variability need not be a major concern for on-going visual assessments, once field observers are trained. We conclude that visual estimates of periphyton cover are promising as a defensible method for estimating the standing crop of periphyton in rivers.

Appendix K Recommended variables and measurement protocols

Table K-1: Variables that we recommend should be measured as part of Regional Council State of Environment Monitoring to enable further development of instream plant and nutrient guidelines, the recommended methods of measurement to facilitate national consistency and the recommended frequency of measurement.

Parameter	Method	Frequency
PERIPHYTON		
Periphyton cover	Determine mean percent cover of algae as filamentous algae , Didymo mats, Cyanobacterial mats, other mats, sludge, thin films, bare area and macrophytes at regular intervals (at least 10 observations in total) across multiple transects in runs using an underwater viewer (bathyscope or black disc viewer with mirror removed). See Kilroy (2011) for guidance on cover assessment.	Weekly to measure growth rates for at least 1 priority site per region and monthly at other sites, Not within 2 weeks of a spate/flood sufficient to scour periphyton (often > 3x median but may be less – use local knowledge if available).
Periphyton biomass: Chl *a* and ideally AFDM & periphyton thickness from settled volume (optional extra to periphyton cover)	At regular intervals (≥5) across a transect collect single stones. Scrub periphyton from all stones (whole stones *or* from 'representative' defined area on each stone) into a small volume of water in a bucket using a stiff nylon bristle scrubbing brush, pour scrubbed material into a single sample tub and store on ice in the dark until returned to the laboratory. For whole stone method, measure a,b,c axes of each scrubbed stone to calculate exposed stone surface area (Biggs & Kilroy 2000; ESA = 1.59 + 0.811(ab+ac+bc)). Measure settled volume in (sample pottles), AFDM and chl *a* of sample by standard laboratory methods. Divide biomass by exposed surface area to calculate biomass thickness and density per m^2.	Weekly to measure growth rates at least 1 priority site per region. At other sites quarterly (linked to monthly cover assessment, see above). Quarterly sampling not within 2weeks of a spate/flood sufficient to scour periphyton (often > 3x median but may be less – use local knowledge if available).
MACROPHYTES		
Macrophyte cross-sectional area or volume	Determine mean percent cross-sectional area or volume of transects occupied by macrophytes. Ideally determine volume of each growth form (i.e., emergent, submerged, surface-reaching) and each species separately. See field sheet in Appendix B. Send samples of any unidentified species to NIWA for identification if necessary. Species identification is necessary to identify the presence of nuisance risk species and for general freshwater biosecurity.	Monthly or at least quarterly. Not within 2 weeks of a spate/flood sufficient to scour macrophytes (probably >3-4 times median flow, see section 3.7.3. but use local knowledge if available).
Dissolved oxygen minima (optional, for researching macrophyte abundance thresholds	Measure dissolved oxygen concentrations at regular intervals (5-30 mins) over a 24 hr period. Use of a calibrated datasonde or other automated logger is best.	At the same time and location as macrophyte measurements.
LIGHT		
Absorbance 340 & 740	Collect a water sample from centre of channel into acid-washed bottle. Chill, keep dark, filter (0.2-micron paper) and analyse sample with standard spectrophotometric method.	Monthly or at least quarterly.
Black disk	Davies-Colley (1988), MfE (1994).	Monthly or at least quarterly.

Parameter	Method	Frequency
Mean depth	1. From calibrated stage recorder; or 2. Multiple transects (≥3) across channel in reach with regular measurement intervals (>5/transect) (i.e., protocol 2, Harding et al. 2009).	Monthly or at least quarterly.
Shade	1. Paired light meters or canopy analysers (Davies-Colley and Rutherford 2005); or 2. Spherical densiometer measurements (Harding et al. 2009). (Densiometers available from Forestry Suppliers Inc. for US$100; www.forestry-suppliers.com; or 3. Visual estimate based on calibrated photos (Fig. 19, Harding et al. 2009).	Quarterly or at least annually in summer.
HYDROLOGICAL		
Discharge	1. From calibrated automated stage recorder, or 2. Measurements across a transect using the cross-sectional area x velocity method.	Daily or at least monthly.
Flow velocity	1. Calculated from mean discharge, depth and wetted widths ; or 2. Multiple transects (≥3) across channel in reach with regular measurement intervals (>5).	Monthly or at least quarterly.
FRE values	Summer and annual FRE1-3 and 7 values. From daily and instantaneous discharge records (e.g., using daily mean and maximum flows) with no filter period between floods (i.e., exceeding 1, 2, 3 x or 7 x median flow, as applicable), or with a 5 day filter period (as used in the New Zealand Periphyton Guideline).	n/a
NUTRIENTS		
Nutrients (DIN and DRP)	Collect a water sample from centre of channel into an acid-washed bottle. Chill, filter (with <0.45-micron paper) and analyse sample with standard nutrient colorimetric methods (detection limit <5 mg m^{-3} for DIN, <1 mg m^{-3} for DRP).	Weekly, monthly or at least quarterly with periphyton/macrophyte measurements.
Sediment nutrients (TN and TP) (not essential parameter)	Only feasible in soft-bottomed streams. Use a small core (5-10 cm diameter) to sample the top 2cm of sediment at regular intervals (≥5) across multiple transects; pool cores as one sample. Homogenise, dry sample at 105°C for 24h and analyse by standard acid digest and colorimetric methods.	Annually in summer.
GRAZERS		
Invertebrate grazers	Quantitative protocol C3P3 (Stark et al. 2001) for benthic invertebrates with analysis of a subsample (made using a Folsom-type sample splitter[2]) yielding a ≥200 individual count from which grazer densities/m^2 can be estimated. See Appendix C for list of invertebrate macrograzer species. In soft-bottom streams, optionally use protocol C2 but with care to record total area sampled.	Annually in summer at least 3 weeks after a 3x median flow event.

[2] The Folsom splitter is a rotating cylindrical drum with a vertical, semicircular partition mounted in the center that splits the sample in half once it is judged to be evenly spread (e.g., http://www.gov.mb.ca/conservation/eal/registries/5583lalor/eba_appendixc_97_136.pdf). A cheap, easy to use version can be made by inserting a partition in a round biscuit container with a see-through window in the lid. The sample is split successively until an amount of material likely to yield ≥200 individuals is produced and the actual densities are estimated by multiplying the taxa counts by the inverse of the subsample fraction.

Parameter	Method	Frequency
Other grazers	1. Perform electric-fishing or netting within the reach to identify fish species present (see David and Hamer 2010 protocols for wadeable streams), or 2. Consult New Zealand freshwater fish database and perform literature search to locate any existing information on herbivorous fish abundance at the site or in the wider river system. 3. Perform a visual count of grazing waterfowl over a specified area.	Annually.
OTHER		
Wetted width	Measure distance across wetted channel at ≥3 locations in reach.	Monthly or at least quarterly.
Substrate size	Substrate Index (Quinn & Hickey 1994), based on either Wentworth size class frequencies from visual assessment or (preferably) Wolman pebble count data (Harding et al. 2009, Parkyn et al. 2010); or visual assessment of % cover of the streambed by Wentworth particle size classes (Table 7, Harding et al. 2009).	Annually in the same season during baseflow conditions.
Water temperature	Measure in main flow (or immediately on sample collected from here) with field temperature meter.	Monthly or at least quarterly.